UNIVERSIDAD DE CÓRDOBA

DEPARTAMENTO DE INGENIERÍA GRÁFICA Y GEOMÁTICA

TESIS DOCTORAL

TECNOLOGÍA OPEN-HARDWARE PARA LA PARAMETRIZACIÓN AMBIETAL EN APLICACIONES DE INGENIERÍA

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Córdoba, 2017

TITULO: *TECNOLOGÍA OPEN-HARDWARE PARA LA PARAMETRIZACIÓN AMBIENTAL EN APLICACIONES DE INGENIERÍA*

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TÍTULO DE LA TESIS:

TECNOLOGÍA OPEN HARDWARE PARA LA PARAMETRIZACIÓN AMBIENTAL EN APLICACIONES DE INGENIERÍA

DOCTORANDO/A:

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Córdoba, 16 de Junio de 2017

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Agradecimientos

A todos los que han colaborado y participado para que este trabajo se pudiera llevar a cabo, puesto que este trabajo no es solo fruto de una persona, sino que han sido muchas personas las que lo han hecho posible.

Me gustaría agradecer y dedicar a mi familia por su apoyo, en especial a mi madre y a mis hermanas.

A todo el departamento de Ingeniería Grafica y Geomática, en especial al área de Geomática, por su ayuda y colaboración, ya que de no ser por su ayuda no hubiera sido posible.

Al Dr. Alfonso García-Ferrer Porras agradecerle todo el apoyo y dedicación que ha tenido y la gran oportunidad que me ha brindado.

Por último, agradecer a el Dr. Francisco Javier Mesas Carrascosa todo el tiempo que ha invertido en este trabajo , ya que gran parte de esta Tesis Doctoral le corresponde.

Gracias a todos

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Abstract

The development of open hardware has provided new tool to improve system to monitor other system. Nowadays the society is immersed in an implementation of systems provide a large amount of data of the environment, which help us to study and understand it.

This doctoral thesis studies the capacity of these free platforms in three differents scenarios as Agronomic, Cultural Heritage and Industrial. A pre-selection of the components and a subsequent verification and validation has been carried out in each of the aforementioned fields.

The result obtained have been positives, being similar to those obtained by commercial equipment. This leads us to the conclusion that these new platforms are the future, not only for its lower price, but for its great capacity of modification and adaptation that the closed commercial platforms do not allow.

Resumen

El desarrollo del open-hardware ha proporcionado una nueva herramienta para mejorar el sistema de monitorización de otros sistemas. En la actualidad la sociedad está inmersa en una implementación de sistemas capaces de proporcionar una gran cantidad de datos del entorno, los cuales nos ayudan al estudio y entendimiento de este.

En esta tesis doctoral se estudia la capacidad de estas plataformas libres en tres campos como son el Agronómico , Conservación Cultural e Industrial. Se ha procedido a una comprobación y una validación posterior en cada uno de los campos anteriormente citados.

Los resultados obtenidos han sido positivos, siendo similares a los obtenidos por equipos comerciales. Esto nos lleva a la conclusión de que estas nuevas plataformas son el futuro, no sólo por su menor precio, sino por su gran capacidad de modificación y adaptación que las plataformas comerciales cerradas no permiten.

Introducción

1. Antecedentes

En la era de la información, la demanda de datos hace que se requiera de sistemas que sean capaces de conceder un vasto conocimiento de cada detalle del mundo actual [1]. La información se ha convertido en un bien de alto valor, siendo almacena para ser procesada y validada [2], ya que el volumen de datos es tan grande que muchas veces se hace imposible el poder trabajar con ésta directamente [3]. Por ello se necesita un proceso de validación de esta información, seleccionando solamente aquella que es necesaria. Esta cantidad de datos recibe el nombre de Big Data [4], correspondiéndose con una cantidad de datos masivos, o macrodatos, que los sistemas de computación normales no son capaces de procesar [5]. Esta inteligencia de datos o datos a gran escala es generada parcialmente por una evolución de los sistemas de transmisión de los datos, como es internet [6].

Hoy en día se habla del internet de las cosas (IOT), que hace referencia a como objetos cotidianos se conectan a internet [7], pudiendo establecer conexiones con otros objetos o usuarios, creando un sistema de comunicación bidireccional entre ambos [8]. Estas conexiones hacen que objetos y personas que están situados a miles de kilómetros, puedan establecer una conexión y un control en tiempo real, facilitando muchas tareas, que antes era imposibles de realizar [9]. El control de sistemas u objetos a través de internet era casi impensable hace unos años, pero el desarrollo de la tecnología ha llevado esta sociedad a una dimensión más tecnificada e interconectada entre sí, un claro ejemplo de todo ello aparece en son las smartcities o ciudades inteligentes [10] o ciudades inteligentes.

Este tema es un concepto que no solo afecta a las comunicaciones, sino al propio desarrollo de una ciudad que posee un control de su entorno muy exhaustivo [11]. Este control se realiza mediante sensores, que ofrecen información muy precisa sobre el entorno, garantizando así una eficiencia y calidad de todos sus sistemas muy superior de las ciudades normales [12]. Un ejemplo seria el sistema de energía, la mayoría de las ciudades, no poseen un control sobre este sistema, teniendo problemas de perdida en algunos sectores y carencia en otros, sin contar los posibles derroches de esta. Un control sobre este sistema, además de proporcionar un buen servicio a todos los usuarios, permite generar un modelo de ahorro energético [13], el cual es indispensable para la sostenibilidad del medio ambiente [14]. Bajo este esntorno de sostenibilidad, otro recurso como el agua, el cual presenta problemas de abastecimiento en la actualidad, puede ser controlado y optimizado para generar un modelo de ahorro y reutilización de este bien tan escaso en algunos lugares.

Para obtener un confort en un emplazamiento se requiere un control de los parámetros de temperatura y humedad [15]. Para esto se necesitan unos dispositivos que sean capaces de medir con precisión variables ambientales y que puedan mandar esa información en tiempo real a un centro de control, para una rápida actuación, y así poder garantizar las condiciones optimas.

Estos sistemas de control se pueden encontrar en el ámbito agrario, elevando a un nivel superior la agricultura tradicional [16]. El empleo de estos nuevos sistemas de sensorización posibilita el desarrollo de nuevas formas más de hacer agricultura de precisión, ofreciendo un control que mejore el rendimiento de los cultivos, además de un ahorro tanto de costes energéticos, agua y materiales usados en el cultivo al considerar la variabilidad espacial presente en la parcela, de este modo, por ejemplo un sistema de control de riego en tiempo real proporciona en todo momento lo que el cultivo necesita en cuanto a dosis de agua [17].

Ante este escenario el precio de la electrónica ha sido siempre un hándicap para su implantación en los todos los entornos que nos rodean [18]. Sobre todo en aquellos en los que su presencia no está especialmente vigilada o supervisada, ya que esta suele ser delicada y de un elevado coste, pudiendo estar expuesta a robos y/o actos vandálicos por parte de terceros. Esto origina que el uso de sensores, microcontroladores y componentes electrónicos en general presenten un uso dispar dependiente de la actividad económica en la que se implementa.

En el campo industrial, la sensorización está muy implantada en procesos de fabricación, montaje y producción. Para ello se usan todo tipo de sensores, con precios y calidades muy diversas, ayudando en el proceso de la actividad que se desarrolla y facilitando y controlando el trabajo [19]. No obstante, aunque en mucho de los procesos se usen una gran diversidad de estos sensores, se pueden encontrar diferentes casos en los que éstos no están adaptados o no están optimizados para la tarea que tienen que desempeñar [20].

Otro campo donde su uso está muy extendido, sobre todo tratándose de obras de arte de alto valor económico y/o cultural, es el del patrimonio histórico. En este caso de uso los sistemas de monitorización suelen ser muy precisos y costosos, permitiendo un control y una monitorización continua de parámetros ambientales fundamental es en la conservación patrimonial de obras de arte. Sin embargo, la mayoría de edificios, monumentos o lugares con valor patrimonial, carecen de algún tipo de control o monitorización pese a que este control es necesario para una adecuada conservación y mantenimiento [21].

Por último, uno de los sectores donde la presencia de sensorización es escasa frente a los descritos anteriormente, es el sector agrario, debido principalmente a las condiciones de uso que presenta. En este caso, la vigilancia de los componentes es complicada, ofreciendo además una elevada exposición a daños tanto por agentes climáticos como por terceros. Esto hace que aparezcan ciertas reticencias a la instalación de sensorización, apareciendo solo en aquellas explotaciones cerradas y/o vigiladas, y en un número de dispositivos reducido, debido principalmente al elevado coste económico de los modelos comerciales que se pueden encontrar en el mercado actual.

En la era de la información y la conectividad, el usuario y/o aplicaciones demandan un aumento de información. El desarrollo de las redes móviles y sistemas de banda ancha favorecen al tráfico de información, haciendo la información accesible independientemente de la localización y momento del día. Esto ha permitido que la presencia de sensorización esté experimentando un aumento de sus uso en escenarios de trabajo tan variado como la agricultura, la domótica o las ciudades entre otros. A modo de ejemplo, el aumento de sensorización en las ciudades ha desvelado un fenómeno conocido como microclimas [22, 23]. En estos microclimas se pone de manifiesto como en dos lugares muy próximos puede presentar condiciones ambientales distintas. Esto puede generar necesidades muy distintas entre estos dos lugares de cara a mantener un cierto nivel de confort adecuado.

2. Open Source Hardware

El Open Source Hardware (OSH) o hardware libre [24] engloba a todas aquellas plataformas que distribuyen de forma libre su diseño, esquemas y especificaciones [25, 26]. La filosofía de este hardware es la fácil manipulación y alteración de su forma original, para adaptarla a las necesidades del usuario [27]. De esta manera, el usuario tiene un control total sobre la plataforma, pudiendo hacer una versión más eficiente para el desempeño del trabajo para que desee orientarlo.

La gran demanda de OSH en los últimos años es resultado de la cultura libre la cual promueve la libertad en modificaciones y distribuciones de trábajos de terceros, en contra de las medidas restrictivas como los derechos de autor de plataformas cerradas, no permitiendo ser modificadas ni alteradas por el autor o fabricante de esta [28].

El mercado del OSH es bastante grande, apareciendo formado por bastantes distribuidores que poseen sus dispositivos registrados, ya sean microcontroladores, sensores o componentes electrónicos. Estas empresas, como Adrafruit Industries (New York, EEUU) o Sparkfun Electronics Bouler, (Colorado, EEUU), lideran este sector, con electrónica que no va solamente dirigida al ámbito empresarial, sino que está pensada como electrónica de consumo en general para que cualquiera pueda hacerse con ésta y hacer sus propios proyectos. Esta nueva plataforma se ha convertido en la piedra angular de muchos centros educativos, ofreciendo una nueva asignatura y una nueva metodología de enseñanza sobre las nuevas tecnologías.

A raíz de este auge, otras empresas han empezado a copiar elementos ya existentes, ofreciendo de forma no oficial un catalogo de productos más variado. Estas copias no originales, están construidas a imagen y semejanza de las principales marcas, y funcionan correctamente, presentando como inconveniente que su control de calidad no está sujeto a ningún estándar y eso puede suponer un problema de estabilidad si se busca un sistema de confianza.

2.1 Arduino

Esta compañía de hardware libre nace con el propósito de ofrecer una plataforma de bajo coste para estudiantes y profesionales que querían empezar en el mundo de la electrónica [29]. La evolución de esta plataforma ha sido vertiginosa en el tiempo, surgiendo diferentes modelos de esta marca, y a su vez siendo copiada y distribuida por otras empresas [28]. Este es el caso de Ferduino, una empresa que se dedica a copiar la placa original Arduino en todos sus modelos, además de ampliar el catalogo de esta

La plataforma Arduino cuenta con un entorno amigable y sencillo, además de miles de esquemas y posibles proyectos publicados en la red para su posterior replica por parte del usuario [30]. Su bajo coste ha hecho que cientos de usuarios la utilicen e investiguen con ella [31], desarrollando nuevas aplicaciones [32]. Su lenguaje de programación se basa en C, soportando algunas funciones estándar de C y algunas de C++.

La versión más común de Arduino está compuesta por el microcontrolador ATmega328, dispone de un AVR 8 bit, con una memoria flash de 32 Kb, y una SRAM de 2Kb. Trabaja a una frecuencia máxima de 20Mhz y tiene un voltaje de operación de 1.8 a 5.5v. Este microcontrolador se puede usar de forma autónoma a la placa completa, ya que esta la placa en realidad es un shield que ayuda a la conexión y alimentación de esta. En muchos proyectos, una vez programado, se desmonta el microcontrolador de la placa y se usa para reducir el consumo de esta.

La programación sobre esta plataforma no requiere de mucha potencia de procesamiento ni de mucha memoria para la programación. No obstante, están apareciendo en el mercado nuevas placas con una mayor potencia y memoria, como es el caso de Intel Galileo. Este modelo Galileo está pensado para la nueva era del Internet of Things (IOT) [33] y el Big

Data [34], el cual necesita si necesita de mayores capacidades y una mayor potencia para el procesamiento de grandes paquetes de información.

2.2. Raspberry Pi

Es un ordenador reducido de bajo coste económico cuyo origen y desarrollo presenta aspecto comunes con Arduino, con la salvedad de ir destinado a otro tipo de usuario [35], ya que su objetivo no es la práctica de la electrónica en sí, sino la enseñanza en computación [36]. Parte de la filosofía de software libre, y pese a presentar alguna limitación de software en sus inicios como la de disponer solo de una versión derivada de Debían llamada Raspbian [37], poco a poco ha ido aumentando el cátalogo de sistemas operativos que se le pueden instalar a este micro ordenador [38]. La fundación que mantiene el registro de esta plataforma, permite su uso libre para uso educativo o particular y no restringe su uso para nivel empresarial [39].

La Raspberry Pi presenta actualmente tres versiones, disponiendo la ultima versión de un procesador ARM de 4 núcleos de 1.2 Ghz de velocidad con una memoria de proceso de 1Gb DDR3. Tiene instalado un procesador grafico VideoCore con OpenGL. No dispone de disco duro para la instalación del sistema operativo, pero dispone de una ranura micro SD para este propósito además de otros puertos como USB o LAN para conectividad avanzada [40]. Su entorno es muy similar a un Linux, y ofrece un rendimiento inmejorable, sirviendo como cualquier otro ordenador, para consultas de internet, reproducción de archivos multimedia o para ejecutar algunos juegos o programas como procesadores de textos [41].

2.3. Sensores

La gran gama de sensores que se encuentra hoy en el mercado hace que casi se pueda monitorizar cualquier aspecto de interés y/o necesidad. Los sensores han y están experiementando una gran evolución, y cada vez existen más modelos, con distintas características, con un abanico de precio muy variado, adaptándose a las exigencias del usuario. Las diferencias principales que presentan entre distintos sensores de una misma tipología están relacionadas con la precisión y su rango de medida.

El campo de uso de estos sensores es muy amplio como la monitorización, de parámetros como temperatura y humedad en smartcities por medio de vehículos unipersonales [42, 43] o en aplicaciones agrícolas [44] para predicción de sequias o producción[45].

El uso de estos sensores en el campo de la conservación del patrimonio tecnifica la zona de actuación, creando una entorno controlado con un desarrollo inteligente del entorno [46]. Esto sensores de código abierto ofrecen una nueva dimensión al mundo de la conservación patrimonial [47].

Por otro lado, el uso de sensores en el sector industrial se ha disparado en los últimos años debido a su precio, creciendo su rentabilidad a un menor coste[48].

La lista de sensores a utilizar es muy amplia, ya que para solamente medir un parámetro como es la temperatura se tienen actualmente más 30 tipos de sensores diferentes, analógicos, digitales, por contacto, sin contacto, ect... Igualmente es posible disponer de sensores, sencillos como temperatura y humedad hasta complicados y sofisticados como aquellos que que miden concentraciones de gases específicos, como halógenos, detectores de objetos, o sensores laser para reconocimiento del entorno que rodea.

3. Conectividad

La conectividad entre dispositivos ha tenido un gran desarrollo gracias a la implantación de la banda ancha móvil. Ésta se ha ido expandiendo en los últimos años abarcando casi todo el territorio nacional en el caso de España [49]. Esta red posibilita conexiones rápidas y con gran capacidad de envío de información en tiempo real, facilitando que una gran red de sensores pueda enviar todos los datos, éstos sean procesados y enviados al usuario final para que pueda operar con ellos [50]. Para que se produzca esta comunicación es necesario que todos los dispositivos estén sujetos a unas normas denominamos protocolos. Los protocolos organizan los diferentes aspectos que intervienen en el proceso de comunicación entre dispositivos de diferentes lenguajes [51].

La conexión entre diferentes dispositivos, como por ejemplo un microcontrolador con unos sensores [52], y este microcontrolador a su vez con un pequeño ordenador, hace que se necesiten protocolos diferentes los cuales establecen la relación entre los distintos lenguajes de los dispositivos que están conectados. Existen protocolos libres, los cuales pueden ser usados de forma libre y con dispositivos sin necesidad de permisos para su uso [53]. En cambio, aquellos protocolos que no son libres solo funcionan en dispositivos que tienen el permiso del propietario del protocolo. Un ejemplo de protocolo libre es el Transmission Control Protocol (TCP), es el protocolo usado para el envío de información entre ordenadores usando internet, este protocolo se usa en cualquier sistema operativo. En cambio el protocolo para red de sensores Wireless Sensor Network (WSN) [54], es un protocolo propietario, el cual solo admite conexión entre dispositivos autorizados por el propietario para establecer una conexión entre varios dispositivos.

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Presentación del trabajo

Esta tesis doctoral se basa en la utilización de hardware de bajo coste en diferentes escenarios de uso como el agronómico, patrimonial y energético, presentando a esta electrónica low-cost como una alternativa fiable a un mercado que se enfrenta a una necesidad de permanente información y monitorización de los sistemas a estudiar. Estas necesidades se ven dificultadas en ocasiones por el coste económico de los sistemas de sensores que existen en el mercado y los protocolos de conectividad de éstos, imposibilitando su modificación o implementación con nuevas versiones que no estén sujetas al propietario del protocolo elegido.

Por este motivo, es necesario un sistema de redes de sensores basados en un protocolo libre, que pueda ser modificado en función de las necesidades y sujeto a ampliaciones e implementaciones con cualquier tipo de sensor del mercado.

La tesis se constituye en tres capítulos que se resumen a continuación

En el **capítulo 1** se presentan los resultados de la experiencia obtenidos en el uso de tecnología low-cost en el campo de la agronomía. Con objeto de la determinación de microclimas se ha desarrollado una estación meteorológica de bajo coste. Para ello se realizó un estudio de cómo estos sensores se comportan a la intemperie, demostrando la capacidad de monitorizar de forma autónoma y sostenible, sin necesidad de alimentación externa distintos parámetros climáticos. El dispositivo fue expuesto a agentes externos como lluvia y granizo, además de ser rociado por productos como herbicidas y otros productos aplicados en la parcela de experimentación. Los resultados obtenidos fueron contrastados con otros equipos comerciales, demostrando la alta estabilidad, fiabilidad y robustez del sistema diseñado.

En el **capítulo 2** los ensayos se realizaron en el ámbito patrimonial, concretamente en la Mezquita-Catedral de Córdoba. En este caso se instalaron varias estaciones para monitorizar diferentes puntos del edificio, comprobando la existencia de microclimas dentro del propio edificio. Para estas pruebas se diseñaron unas estaciones con sensores de temperatura, humedad y luminosidad, las cuales almacenaban datos en una tarjeta de memoria cada 2 segundos. Se instalaron 14 estaciones cubriendo distintas zonas del edificio, demostrando la existencia de distintas zonas con condiciones climatológicas distintas dentro del mismo. Se crearon mapas de temperatura y humedad los cuales sirvieron para el estudio de las variables que condicionan los microclimas dentro del edificio. Los resultados de este trabajo mostraron la capacidad y eficiencia para crear una red de sensores para monitorizar diferentes zonas, arrojando datos muy significativos de las condiciones ambientales del interior del edificio.

En el **capítulo 3** los ensayos se realizaron en el campo industrial, más específicamente en una central termoeléctrica. En este caso se diseñó un dispositivo el cual pudiera georeferenciar los datos registrados por un sensor termográfico. Para ello se dispuso un sistema compuesto por varias plataformas libres con diferentes protocolos, los cuales registraban la posición y actitud en el espacio del sensor, facilitando las labores de inspección en centrales. Como conclusión de este tercer capítulo se establece el aumento de prestaciones que se puede ofrecer a otros sensores.

Objetivos

Los objetivos de la presente tesis doctoral son los siguientes:

1. Selección y validación de los sensores utilizados para el diseño de los dispositivos. Una vez elegidos se procederá a un proceso de calibración y comprobación de su correcto funcionamiento.

2. Creación de una aplicación de estos sensores en el campo de la Agronomía. Se creará una metodología específica para este campo, y se procederá a la validación del mismo.

3. La implementación de una aplicación de los sensores en el campo del Patrimonio Cultural. Se procederá al estudio y validación de éstos como red de sensores para la creación de un mapeado de temperatura y humedad, para el estudio de los microclimas en edificios.

4. El desarrollo de una aplicación de los sensores en el campo Energético, con desarrollos de otros subsistemas que no son open-hardware. Además de plantearse una metodología para inspección, se procederá a su validación y a ladeterminación de las las ventajas que ofrece frente a sistemas tradicionales.

Capítulo I

Open source hardware to monitor environmental parameters in precision agriculture

Abstract

Precision agriculture combines the use of information and technology to ensure the best agricultural practices. Obtaining real-time non-invasive information to monitor crops or make yield predictions is a challenge. An approach is to use crop yield models in combination with real-time data used as input in such models. It was demonstrated that it is possible to design an accurate system using open source hardware and open systems to record the input for these models and monitor crops. The system presented has two main components: a device that records environmental parameters and a smartphone application (software) that links this device to a data server in order to process and analyse the information. The solution is scalable in terms of the type of sensors used (i.e. temperature and relative humidity of the air or soil), the rate of information retrieval and so on, so it can be used in various scenarios, including environmental or land policy monitoring. Moreover, this open source hardware can be used by a broad variety of users and is an alternative in poor rural areas because of its low cost compared to other solutions. It can enable increased agricultural production and management of the local environment, bringing new agricultural practices to these areas. Furthermore, progress in the use of this type of technology can help to develop new capabilities for growers. Results of calibration tests and measurements to demonstrate the usefulness of this system in precision agriculture are presented.

Resumén

La agricultura de precisión combina el uso de la información y la tecnología para asegurar las mejores prácticas agrícolas. Obtener información en tiempo real no invasiva para monitorear los cultivos o hacer predicciones de rendimiento es un desafío. Un enfoque consiste en utilizar modelos de rendimiento de cultivos en combinación con los datos en tiempo real para hacer un pronóstico de dichos modelos. En este estudio se demuestra que es posible diseñar un sistema preciso usando open hardware y sistemas abiertos para registrar la entrada de estos modelos y monitoriza los cultivos. El sistema presentado tiene dos componentes principales: un dispositivo que registra parámetros ambientales y una aplicación de smartphone (software) que vincula este dispositivo a un servidor de datos para procesar y analizar la información. La solución es escalable tanto en el tipo de sensores utilizados (temperatura y humedad relativa del aire o del suelo), como la cantidad y el tipo de información que se qnecesite, etc., por lo que puede utilizarse en diversos escenarios, incluyendo la monitorización ambiental o de las políticas agrarias. Por otra parte, este hardware de código abierto puede ser utilizado por una amplia variedad de usuarios y es una alternativa en las zonas rurales pobres debido a su bajo costo en comparación con otras soluciones. Puede permitir un aumento de la producción agrícola y la gestión del medio ambiente local, llevando nuevas prácticas agrícolas a estas áreas. Además, los avances en el uso de este tipo de tecnología pueden ayudar a desarrollar nuevas capacidades para los productores. Se

presentan los resultados de las pruebas de calibración y las mediciones para demostrar la utilidad de este sistema en la agricultura de precisión.

1. Introduction

Precision agriculture (PA) can be considered as the art, and science, of using advanced technology to enhance crop production. Its main goals are to tailor management practices to a crop considering the conditions of the site and to improve field management in order to minimise diseases and pests and consequently reduces the use of pesticides, leading to more efficient and environmentally acceptable agriculture (Blackmore, Wheeler, & Earl, 1996). Therefore, PA can be considered as a management strategy that uses information technology with the aim of improving production and quality (Valente et al., 2011). Obtaining real-time non-invasive information to monitor crops or make yield predictions is a challenge in agriculture. Crop models (CMs) offer reliable results and are interesting tools in PA, supporting decision-making in agriculture (Ewert et al., 2011). Climatic data are often the most important input data in CMs. Specifically, air temperature and precipitation are the most important climatic variables that influence yield (Porter & Semenov, 2005).

Even when mean values are used, predictions can be affected by fluctuations in temperature and/or precipitation (Semenov & Porter, 1995). The accuracy of CMs depends on the degree of knowledge of the weather conditions. This knowledge can be associated to a local area and even to an individual plot when the damage caused by frost in some crops is related to minimum temperatures that depend on the location and aspect of the plot. Under such scenarios it is necessary to determine environmental parameters for a specific plot. For example, crops such as tea are highly sensitive to these circumstances (Lou & Sun, 2013). In those situations, a specific plot may be affected by frost while a neighbouring plot may not. To determine the values of climatic variables, some regions have public weather station networks whose data are accessible to users. Although this information is useful, such stations are often remote from experimental sites and in-field environments (Bellocchi, Rivington, Donatelli, & Matthews, 2010), which reduces the usefulness of the data they provide. Moreover, the information usually refers to a broad area, so it is not possible to monitor different sectors in a plot using a network of sensors.

Recent progress in electronics, wireless communications and production of small size sensors provides new opportunities to monitor and control homes, cities, crops and the environment (Vieira, Coelho, da Silva Jr, & da Mata, 2003). Wireless sensor network (WSN) technologies are the greatest driver of the development of precision agriculture. WSNs comprise several components called nodes. WSN nodes are smart devices that contain several sensors. A sensor is a device that is able to measure physical attributes and convert them into signals for the user. Sensors are the essential components of WSNs and therefore of the overall system for environmental monitoring and control. The development of WSN applications in PA makes it possible to increase efficiency, productivity and profitability while minimizing impacts on wildlife and the environment (Srbinovska, Gavrovski, Dimcev, Krkoleva, & Borozan, 2015).

Such sensor networks have three basic functions: sensing, communicating and computing. Wireless communication technologies such as WiFi, Bluetooth or Zigbee can be used and each have different properties and capabilities such as data rate, range or cost. In PA, sensors and their networks are being used in fertilisation (Cugati, Miller, & Schueller, 2003; He, Wang, He, Dong, & Wang, 2011), irrigation (Vellidis, Tucker, Perry, Kvien, & Bednarz, 2008; Yunseop, Evans, & Iversen, 2008), horticulture (López et al., 2011; López Riquelme et al., 2009), greenhouse farming (Ahonen, Virrankoski, & Elmusrati, 2008; Zhou, Yang, Guo, Zhou, & Wang, 2007) and monitoring of livestock and pastures (Andonovic et al., 2010; Ru, Huan-Sheng, & Bai, 2011).

Data provided by weather stations located near plots are useful to obtain a good description of climatic variables. Although several solutions are described in the literature or available on the market, their functionality is usually limited as their cost is high and they have constant maintenance issues (Gaddam, Al-Hrooby, & Esmael, 2014). Open source hardware (OSH) can be an alternative to such solutions. PA is largely used in the context of large farms and usually implies soil monitoring. In developing countries, such technologies are used in greenhouse farming but have not been used so far in open farms by farmers with small and marginal holdings (Babu, 2013).

In contrast to open source software (OSS), OSH is quite new (Faugel & Bobkov, 2013). One of the most popular examples of OSH is Arduino. It was created in 2005 at the Interaction Design Institute, Ivrea, Italy as a system that allowed students to develop interactive designs. Arduino consists of a microcontroller set on a small printed circuit board; it is fitted with sockets to allow connection with external devices with digital and analogue input and output (Koenka, Sáiz, & Hauser, 2014). Soon after its creation, Arduino started to be used in hobby projects such as drones and robots (Bin & Justice, 2009; Ross, 2014) or 3D printers (Kostakis & Papachristou, 2014),but scientific applications quickly followed. Arduino has been used for a broad range of applications such as monitoring radiation levels at nuclear facilities (Gomaa, Adly, Sharshar, Safwat, & Ragai, 2013), biomedicine (Kornuta, Nipper, & Brandon Dixon, 2013) and pharmacology (Thomson & White, 2014). Several authors have used Arduino to monitor ambient conditions such as temperature or humidity. Gomes et al. (2011) measure and predict temperature, Rodriguez et al. (2011) monitor temperature of data centers and Barroca et al. (2013) measured temperature and humidity inside structures.

The development of OSH is often for commercial markets and thus may have the stability, ruggedness, accuracy, for other applications. In this study a prototype of a system that is able to provide PA services based on OSH is presented. The main purpose of this system is to measure infield environmental parameters to use as input in CMs: temperature and humidity of air and temperature and humidity of soil. This paper focuses on the design, implementation and validation of the system. Survey data are presented to assess the usefulness of the system, comparing it to data from a proprietary weather station.

2. System overview

Figure 1 shows the conceptual model of the system. It had three main elements: a weather station developed with open source hardware (OSH-WS), a communication channel and a database. These three components worked together to generate a useful monitoring environmental system. The system was scalable and it was possible to include other sensors and/or communication technologies. The present study only deals with one of the possible solutions: a way to record environmental parameters minimizing financial costs. The weather station consisted of several sensors that record environmental parameters such as soil moisture and temperature and air humidity and temperature. This information was uploaded to an open-source database using a communication channel. In this study, a smartphone was used to collect data and, using Bluetooth communication with georeference, to upload the information to a server. This information could be used to generate PA services, develop maps or support decision-making. Users could obtain real-time information about the data recorded through a smartphone.

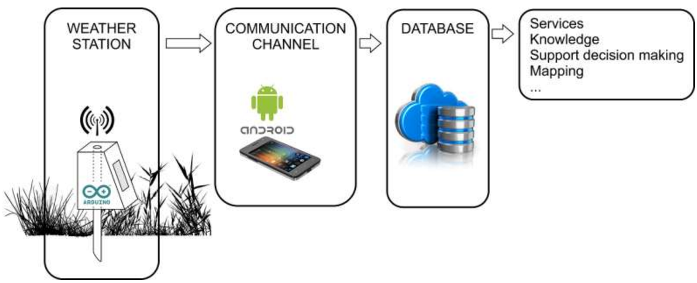


Fig. 1. Conceptual model of the system

3. Hardware description

The proposed system is based on the Arduino platform (www.arduino.cc). Arduino is a single-board microcontroller based on easy-to-use hardware and software. It is a descendant of the open-source Wiring platform and is programmed using a Wiring-based language similar to C++. Arduino boards can be purchased as pre-assembled or do-it-yourself kits, and hardware design information is available. In this work the Arduino MEGA ADK, a microcontroller board based on the ATmega2560 chip (Atmel, Datasheet 2560) was used. It has 54 digital input/output pins, 15 of which can be used as pulse width modulation outputs with 8-bit resolution. Moreover, it has 16 analogue inputs that provide 10 bits of resolution. The ATMega2560 also has a 16 MHz crystal oscillator, a USB connection, a power jack and a reset button. It uses a flash memory of 256 KB with 8KB used for boot loading, 8KB of SRAM and 4 KB of EEPROM. A picture of the Arduino MEGA ADK is shown in Fig. 2.

Fig. 2. Picture of an Arduino MEGA ADK board used to develop the weather station.

The role of the microcontroller is to manage, arrange, store and transmit the onboard sensor data. A large number of sensors are available to monitor and measure many types of environmental parameters. Table 1 summarises the sensors used to measure air temperature and humidity, soil moisture and soil temperature, presence of light and time reference data and store such data. In order to verify that the sensors worked properly, they were calibrated taking into account local environmental conditions. The sensors' accuracy were similar to professional sensors used in environmental monitoring network (Hoogenboom, 1993).

Table 1.
Summarised description of the sensors used.

ID of sensor	Description	Function
LM35	Analogue temperature sensor	Record soil temperature
DS18B20	Digital temperature sensor	Record ambient air temperature
KEYES	Analogue humidity sensor	Record soil moisture
DHT22	Digital humidity sensor	Record ambient humidity
EDC-307792	Light sensor module	Record presence of light
AMS1117	SD card slot	Store measurements
DS1307	Real-time clock module	Take time reference measurements
JY-MCU H06	Bluetooth sensor	Link with smartphone
RadioShack P1560	Photovoltaic panel	Supply energy

3.1. Temperature

Temperature is one of the most common variables measured in many disciplines and is basic in CMs. Analog and digital measurement technologies are available. In the former, electrical resistance changes in response to temperature, while digital sensors are designed to interface with microcontrollers and computers. In the present study, the analogue sensor LM35 (Texas Instruments Inc., TX, USA) was used to measure soil temperature. This sensor operates in a -55 °C to 150 °C temperature range and has an accuracy of 0.5 °C at 25 °C. The DS18B20 (Maxim Integrated, San Jose, CA, USA) is a digital thermometer that provides 9-bit to 12-bit Celsius temperature. This sensor operates in a range -55 °C to 125 °C. Between -10 °C to 85 °C it has an accuracy of 0.5 °C and was used to measure air temperature. Both sensors were calibrated using a Hanna Instrument HI 93531R (Hanna Instruments, S.L., Guipúzcua, Spain), a high accuracy thermometer with a resolution of 0.1 °C. Ten measurements were taken every five minutes to compare values. The maximum error did not exceed 5 % of the real value obtained by the LM35. Figures 3(a) and 3(b) show the results of the comparison of both sensors taking the HI 95351R as a reference. This information was used to describe the temperature recorded by the sensors more accurately.

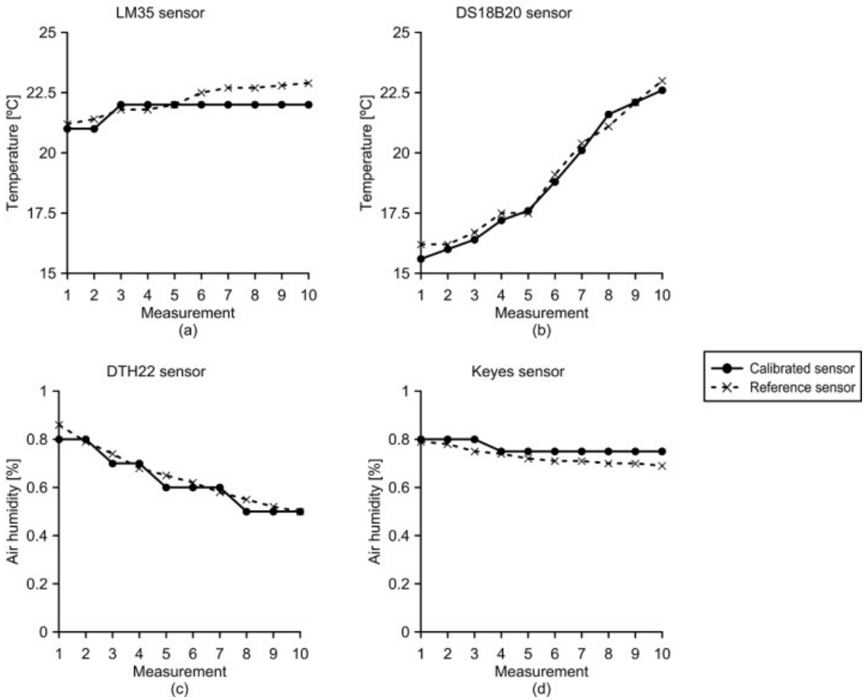


Fig. 3. Comparative graph between calibrated and reference sensors: (a) soil temperature, (b) air temperature, (c) air humidity and (d) soil moisture.

3.2. Humidity

Water availability and moisture status is a very important parameter in agriculture. Analogue and digital sensor technology was used in the system. Air humidity was measured with a DHT22 digital sensor (Aosong Electronics Ltd., Guangzhou, China). The DHT22 sensor was made of two parts: a capacitive humidity sensor and a thermistor. This sensor proved to be reliable and stable. The output of the DHT22 was a calibrated digital signal that was interfaced directly to the Arduino port pin. It used an exclusive digital signal collecting technique and humidity sensing technology that was automatically calibrated. DHT22 operates in a 0 % to 100 % range of relative humidity with an accuracy of 2 % and a resolution of 0.1 %. As with the temperature sensor, it was calibrated with the DHT22 using the same procedure. Ten measurements were taken using a five-minute time interval. A PCE-222 environmental meter (PCE Instruments Ltd., Southampton, Hampshire, United Kingdom) was used as a reference. The maximum error ranged from 3 to 7 % of the real value. Figure 3(c) shows the results of this comparison.

To measure soil moisture a Keyes soil moisture sensor was calibrated in order to verify the accurate operation of the device. A sample of soil was taken and moisture levels were changed regularly. The sample was exposed to heat in order to eliminate the moisture. This allowed us to simulate a dry, arid soil environment. Similarly, the sample was watered to various levels and the output of the sensor was recorded. Ten intervals between 0 and 100 % relative humidity were defined. Each interval was measured five times. Validation was performed using a FieldScout TDR 100 soil moisture meter (Spectrum Technologies, Inc., Aurora, CO, USA). The results are shown in Fig. 3(d).

3.3. Other sensors and modules used

All the data recorded had a temporal reference obtained by the DS1307 (Maxim Integrated, San Jose, CA, USA) real-time clock module. This device was a low power, full binary-coded decimal clock/calendar plus 56 bytes non-volatile SRAM.

The information is stored on an SD card as a backup. Once the information was recorded and stored by the OSH-WS, the next step was to upload it to a database. Different technologies could be used for this purpose. A possibility was to use a 3G/4G module, which requires a specific telephone contract. If the system is to be used to monitor a region, several devices will be required to work independently, which makes the solution expensive. In addition, telephone coverage cannot be guaranteed in some locations. The system proposed was to upload information using a smartphone linked to the device by a Bluetooth module. This solution allows users upload information in real time once it is obtained by the smartphone, or, if there is not an adequate coverage, the users can upload later when they have coverage. As the smartphone receives the data, the Global Navigation Satellite System (GNSS) sensor is activated, providing coordinates to the information. This solution was chosen to reduce the financial cost of the system, although it is possible to add a GNSS sensor module or other sensors to the system that increase its capabilities.

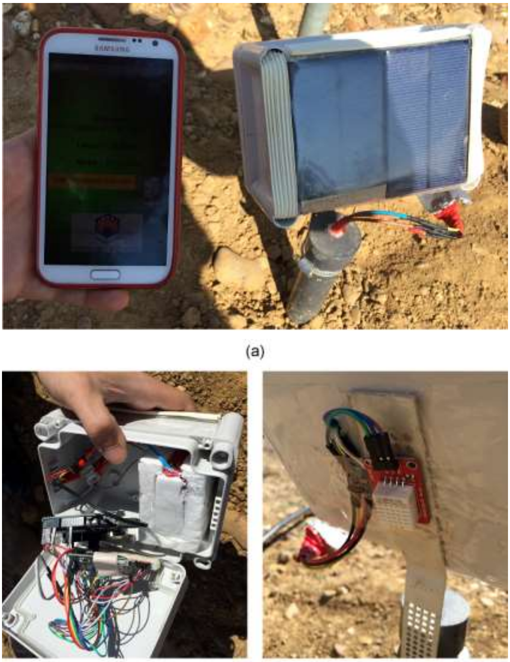
To supply energy to the system, a small RadioShack P1560 solar panel was used, which provides continuous activity of the system avoiding switch-offs or malfunctions.

4. Integrated development environments

Two different integrated development environments (IDEs) were used to program the Arduino and the smartphone application. The IDE used to program the Arduino was 1.0.5-r2. The programming language is a version of C++ adapted to program hardware. The IDE used to develop the smartphone application was Android Studio version 0.4.6 (Smyth, 2014), the official IDE for Android application development. It is based on IntelliJ IDEA and its program language is Java. An application was developed to link the OSH-WS to the smartphone. With this application, users can retrieve the parameters that are being recorded in real time when near to the OSH-WS using Bluetooth communication. Moreover, the application uploads all the new values recorded from the last time to a database. Finally, the GNSS sensor of the smartphone was used to assign coordinates to the OSH-WS.

5. Prototype design

The OSH-WS frame was composed of a box and a tube where exterior and interior sensors can be placed to record the target data. The box was an outdoor waterproof case that protects the sensors from the elements. The solar panel was placed at the front of the box. The case had a low-tilt angle to better orient the solar panels in relation to the sun (Fig. 4(a)). Sensitive elements such as the battery, clock, SD card, Bluetooth sensor and Arduino microcontroller were placed inside the case (Fig. 4(b)). The inside of the case was easy to access to change or manipulate the connections. The sensors used to record air temperature and humidity were placed at the rear of the case (Fig. 4(c)). Exterior elements such as sensors and cables were protected from attack by birds. In addition, the tube was used to place moisture and temperature sensors in order to monitor soil variables. Its length was about 300 mm.



(a)

(b) (c)

Fig. 4. Overview of the OSH-WS: (a) Details of the solar panels, (b) interior of the outdoor waterproof box and (c) details of the air temperature and humidity sensors.

6. Case study and experimental results

Several experiments were performed at the School of Agricultural and Forestry, University of Córdoba, Spain, with the purpose of demonstrating that the proposed system provides quality data. The weather station was set up in an olive grove (37° 56' 8.26'' N, 4° 42' 59.9'' W, WGS84) (Fig. 5). The area has typical continental Mediterranean climate, characterised by long dry summers and mild winters, and a relatively flat relief.

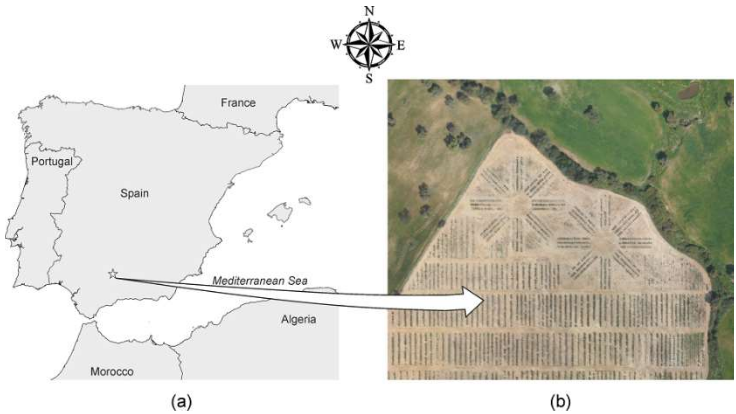


Fig. 5. Overview of the study site. a) Location of Cordoba, b) partial overview of the experimental site.

The first experiment performed was devoted to measuring climate data and comparing them with those recorded by a professional weather station. The aim was to determine the accuracy of the sensors used by the OSH-WS. A Davis Vantage Pro2 weather station (Davis Instrument Corp., Hayward, CA, USA) was used to obtain reference values for climate data. This weather station was equipped with a three-cup anemometer and air temperature and humidity sensors. Air temperature was measured from -40 °C to 65 °C and air humidity was measured from 0 % to 100 %. It had an accuracy of 0.5 °C in air temperature measurements and 3 % in air humidity measurements. Both weather stations were placed together to record data under the same conditions (Fig. 6). They took measurements for three hours, recording data every five minutes, with a total of 36 measurements. Figure 7 summarises the data recorded by both systems for air temperature and humidity.

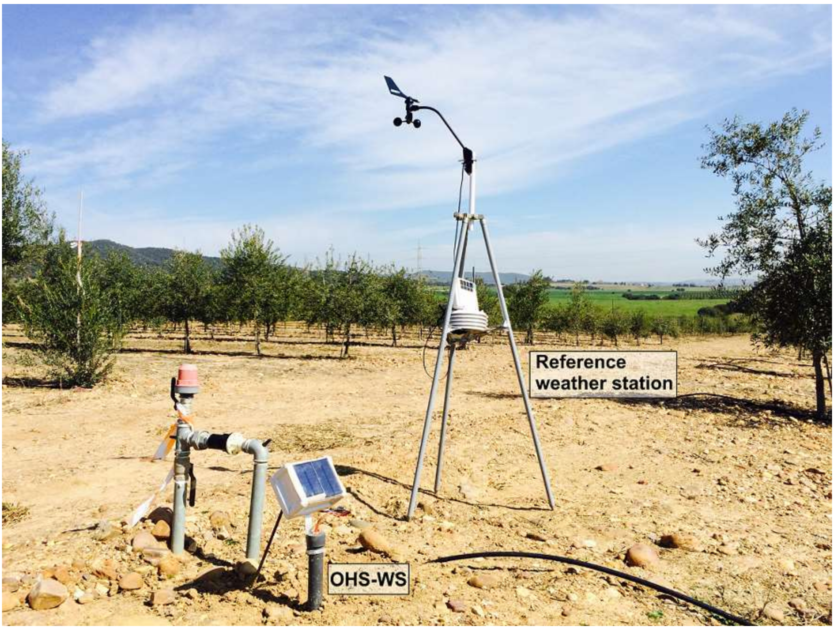


Fig. 6. The two weather stations working simultaneously: the OSH-WS (left) versus the reference weather station (right).

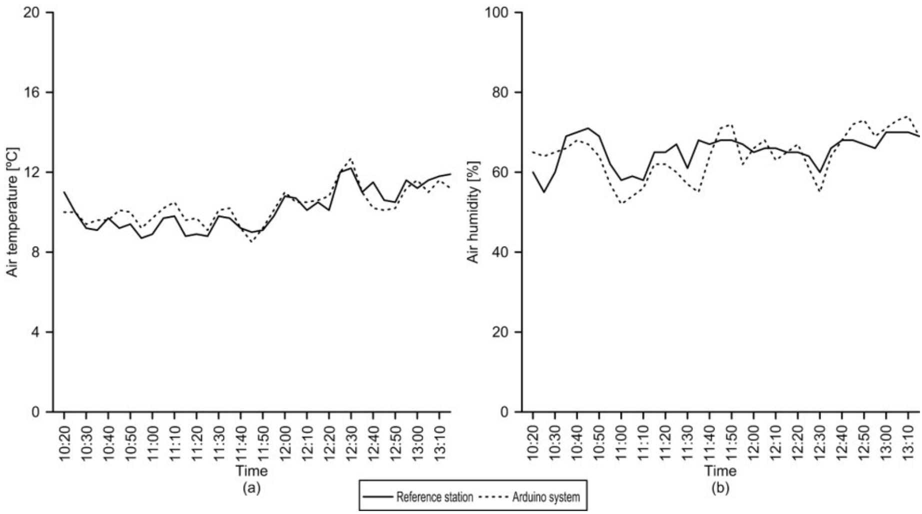


Fig. 7. Comparison between the professional weather station and the OSH-WS: (a) air temperature, (b) air humidity.

Both weather stations were explored to explore the relationship between the data they provided. As regards air temperature, the mean difference was 0.3°C and root mean square error (RMSE) was ±0.7 °C. For air humidity, the results were 1.16% mean error and ±5.2 % RMSE. The OSH-WS did not show any bias in either climatic variable ($P<0.05$) as determined by Student's test. A one-way analysis of variance (ANOVA) test was performed ($P=0.05$) to analyse variance between systems. The tabulated F value obtained from the F distribution considering degrees of freedom 1 and 70 between groups and within groups respectively was equal to $F(1,70) = 3.97$. The calculated F values for temperature and humidity were

1.84 and 1.75. These values were less than the tabulated value and therefore no significant differences between both systems were obtained. Based on these results, the OHS-WS provides good quality information at the same level as the reference weather station.

Because of the broad types of crop models, it is recommend to study each individual crop model to identify their relative strengths in dealing with different types of climate model error (Watson & Challinor, 2013). Air temperature is one of the main variables driving plant development. Sensitivity studies like Ruget et al. (1995) have shown that a systematic error of ±1 °C per day on air temperature along the cultural cycle of the corn generates an error from 0.5 to 1 t ha^{-1} for yield estimation. Under these conditions, the information related to air measurements recorded can be used a priori as a valid input in crop models.

The second experiment performed was devoted to assessing the endurance and consistency of the OSH-WS working in outdoor conditions for a long period of time. In addition data were compared with those registered by an environmental monitoring network. The system was operated 24 hours per day for 23 days recording information every hour. Figure 8 summarises the values recorded for each climatic variable. The plot was visited every week to collect information to upload to the database. Figure 8 shows how the sensors of the OSH-WS worked in a continuous mode, recording information and storing them in a database. At the end of the experiment it rained for three days and its consequences were registered by the sensors. During this period, air humidity (Fig. 8(a), interval from 470 to 510 h) shows an increase in value as a result of the rainfall and the graph does not show the cycle behaviour of the previous days. In addition, because of rainfall, air temperature (Fig. 8(b)) shows a reduction of value while soil moisture (Fig. 8(c)) increase its values and it remains constant on this interval of time. Finally soil temperature (Fig. 8(d)) remained constant over this period of time. Therefore, the sensors of OSH-WS registered the effects of weather conditions.

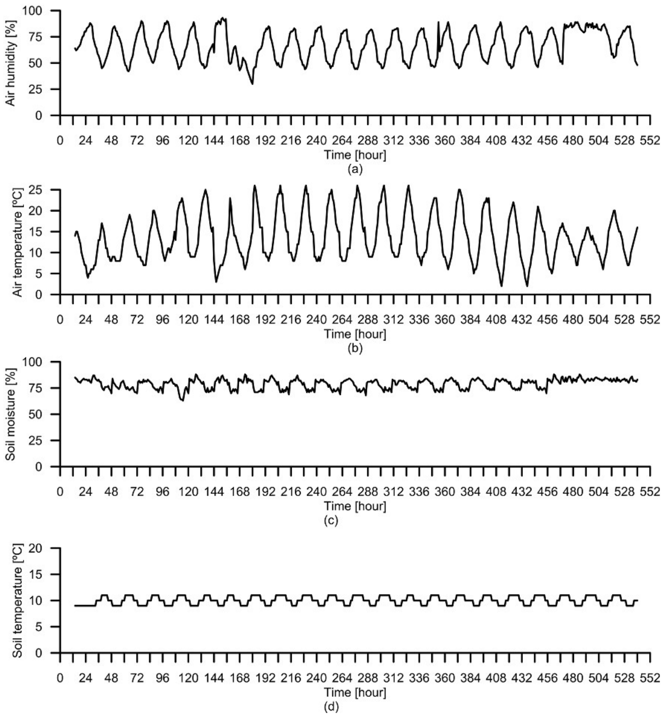


Fig. 8. Results obtained by the OSH weather station: (a) air humidity, (b) air temperature, (c) soil moisture and (d) soil temperature.

During the second stage, data registered by OSH-WS were compared to a particular weather station from an environmental monitoring network 15 km from the test station. This network publishes a daily maximum, minimum and mean value of air temperature and humidity among other parameters. Table 2 shows data of parameters registered by this weather station for the period of time of interest. Comparing daily data the RMSE of maximum, minimum and mean air temperature were ±2.1 °C, ±3.1 °C and ±2.4 °C respectively. Referring to air humidity, RMSE was equal to ±6.1 %, ±6.2 % and ±6.9 % for maximum, minimum and mean values. Therefore, there were significant differences to take into account in crop models (Ruget et al., 1995). These differences are motivated because the environmental network provides input climatic data but weather stations are not able to locally reflect the climate necessary to interpolate data (Monestiez, Courault, Allard, & Ruget, 2001). As a result, the OSH-WS provided local environmental climatic data for a specific plot.

Table 2.
Input climatic data from the environmental network monitoring weather station: maximum. minimum and mean air temperature and humidity.

	Air temperature			Air humidity		
Date	Max. (°C)	Min. (°C)	Mean (°C)	Max. (%)	Min. (%)	Mean (%)
18/02/2015	17.9	6.7	12.2	83.9	40.4	61.8
19/02/2015	17.5	6.4	11.1	83.0	33.3	63.4
20/02/2015	17.9	2.6	10.0	97.9	35.4	70.4
21/02/2015	14.7	4.8	9.4	100	77.5	93.3
22/02/2015	17.2	4.2	9.6	100	42.2	82.7
23/02/2015	17.5	6	11.2	100	58.7	85.3
24/02/2015	19.6	4.7	11.7	100	44.1	79.1
25/02/2015	19.2	4	11.5	100	48.0	80.1
26/02/2015	20.8	4.1	12	100	50.3	82.2
27/02/2015	24.4	5.9	13.6	100	48.0	81.9
28/02/2015	23.2	5.5	14.1	100	45.7	80.4
01/03/2015	22.6	8.1	14.4	100	36.7	76.5
02/03/2015	18.0	4.8	11.6	87.8	23.4	45.3
03/03/2015	21.3	2.2	10.6	93.3	20.5	57.5
04/03/2015	22.6	0.3	10.5	97.8	16.6	60.8
05/03/2015	25.9	3.2	13.1	93.4	22.8	61.9
06/03/2015	25.8	3.7	13.4	97.8	22.1	64.7
07/03/2015	26.3	5.9	13.9	96.6	16.0	65.9
08/03/2015	26.1	5.4	14.3	98.9	21.6	65.1
09/03/2015	24.5	4.0	14.1	100	28.6	69.1
10/03/2015	19.9	6.3	12.4	100	39.7	77.4
11/03/2015	19.8	3.9	12.2	100	24.9	61.7
12/03/2015	19.2	3.6	11.3	73.3	20.6	47.8

7. Practical implementation

The proposed system implemented, with the OSH, can be customised according to the needs of users or organisations. Compared to proprietary solutions, it is possible to choose (i) the sensors that will be used and (ii) the mode of operation of such sensors. As regards sensors, it is possible to add new sensors such as GNSS sensors, communication modules, CO2 sensors, etc. At the same time, users can decide how the information will be stored or transmitted. They can set up the OSH-WS to store and transmit information considering a specific time interval (every hour, half hour, etc.) and also select the accuracy of data. Therefore, the solution could be adapted to the technical characteristics of individual projects and is not a closed solution.

In addition to the technical features of the proposed system, another important advantage is its low cost, which does not exceed 100 €. This could facilitate the development of low cost sensor networks based suitable for poor rural areas. Individual farmers could use this system, collecting in-field data to improve their production and share data with their professional advisors. Likewise, government agencies could use the system to monitor the influence of agriculture policies, environmental parameters, and so on.

8. Conclusion

A system to monitor climatic variables using OSS and OSH to be applied in PA was developed. OSH characteristics such as low acquisition cost and easy customisation can eliminate obstacles associated with proprietary solutions. The proposed system was designed as an alternative to higher cost systems, improving the quality of agricultural production and decreasing management costs.

An OSH makes it possible to implement specific applications that are tailored to the final users. Its software development environment has a larger number of libraries, which facilitates the implementation of standard applications. Environmental parameters such as temperature and humidity can be continuously monitored in order to ensure optimal crop conditions. These technologies offer new possibilities for poor rural areas to improve production farming, environmental management and the monitoring of agricultural policies.

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Monitoring heritage-buildings with open source hardware sensors: a case study of the Mosque-Cathedral of Córdoba

Abstract

A number of physical factors can adversely affect cultural heritage. Therefore, monitoring parameters involved in the deterioration process, principally temperature and relative humidity, is useful for preventive conservation. In this study, a total of 15 microclimate stations using open source hardware were developed and stationed at the Mosque-Cathedral of Córdoba, which is registered with UNESCO for its outstanding universal value, to assess the behavior of interior temperature and relative humidity in relation to exterior weather conditions, public hours and interior design. Long-term monitoring of these parameters is of interest in terms of preservation and reducing the costs of future conservation strategies. Results from monitoring are presented to demonstrate the usefulness of this system.

Resumen

Una serie de factores físicos pueden afectar negativamente al patrimonio cultural. Por la monitorización de los parámetros involucrados en el proceso de deterioro, principalmente la temperatura y la humedad relativa, son útiles para una conservación preventiva. En este estudio se desarrollaron y colocaron un total de 15 estaciones metereológicas utilizando open-hardware en la Mezquita-Catedral de Córdoba, que está registrada en la UNESCO por su sobresaliente valor universal, para evaluar el comportamiento de la temperaturas interiores y la humedades relativas en relación con las condiciones climáticas exteriores, su relacción con la apertura al público y el diseño del interior. El monitoreo a largo plazo de estos parámetros es de interés en términos de preservación y reducción de los costes de futuras estrategias de conservación. Los resultados de la monitorización se presentan para demostrar la utilidad de este sistema.

1. Introduction

Cultural heritage is our legacy from the past and depending on its nature, defined climatic conditions need to be maintained for optimal conservation and to avoid deterioration [1]. Therefore, monitoring microclimatic conditions is important in preventing deterioration of artwork or structural architecture [2,3]. Microclimatic monitoring is a useful tool for the protection of works of art in museums or archives[4], as well as for monitoring structures hosting cultural heritage such as frescos [5]. Its usefulness has also been demonstrated in measuring fluctuations in temperature, relative humidity and in its capacity to alert of the presence of soluble salts or microbiological agents, among others [6].

The interest in monitoring climatic parameters using technological components in cultural heritage is growing [7]. Further methods are being employed more and more frequently to study and preserve cultural properties [8,9].

In this context, climatic variables in cultural heritages have been successfully monitored [10,11], to develop energy savings strategies in museums [12], analyze the impact of lighting and people [13], control physical parameters of interior environments of museums [14] or tombs [5], among others. In general, extreme variations in temperature or relative humidity may cause damage or deformation to heritage works like wood panels or frescoes [15]. Therefore, early detection of anomalies is essential to their preservation [16].

Recent progress in electronics, wireless communications and the production of small sized sensors provide new opportunities to monitor and control homes, cities, crops and the environment [17]. The number of studies demonstrating the value of the preservation and care of cultural heritage is increasing as well [18,19]. On conserving cultural heritage, the application of technology offers useful advantages [20]. It allows the registration of data with a frequency of a data per day, per hour or more [18,21]. Monitoring in higher frequencies (1 datum/minute) is interesting because of the greater recording potential of valuable information which leads to greater accuracy for statistical analysis [22]. Additionally, current electronic devices are smaller and more accurate and easier to keep hidden from spectators, permitting focus to be kept on the artwork [23].

Some authors use commercial data loggers like Hobo [24], DS1922L [25] or DS1923 [26]. The hardware and software of these commercial devices are not open source and therefore cannot be modified [27]. Open Source Hardware (OSH) can be an alternative when customization is necessary. Although OSH is quite new [28] it is being used for different applications in agriculture [17], pharmacology [29] and monitoring radiation [30], among others. In reference to cultural heritage, some researchers have developed data acquisition systems, for example, [31] designed a system for the remote control analysis of wall paintings using ARDUINO technology.

This manuscript describes a system which registers microclimate parameters to be used in preventive conservation of heritage buildings.

Its practicality is demonstrated in its application to the Mosque-Cathedral of Córdoba (Spain).

The article is divided in the following sections: in Section 2, we present a brief description of the study area. In Section 3, we describe the technology, materials and methods used to set up the monitoring system. In section 4, some field tests and their results are presented, followed by a conclusion.

2. Description of the Mosque-Cathedral of Córdoba

Córdoba (Spain) was the capital of al-Andalus for three centuries, housing the largest mosque west of the Moslem world. The Mosque-Cathedral of Córdoba (37° 52' 43'' N, 4° 46' 46'' W, WGS84) (Figure 1) is registered with UNESCO (United Nations Educational, Scientific and Cultural Organization) for its outstanding universal value.

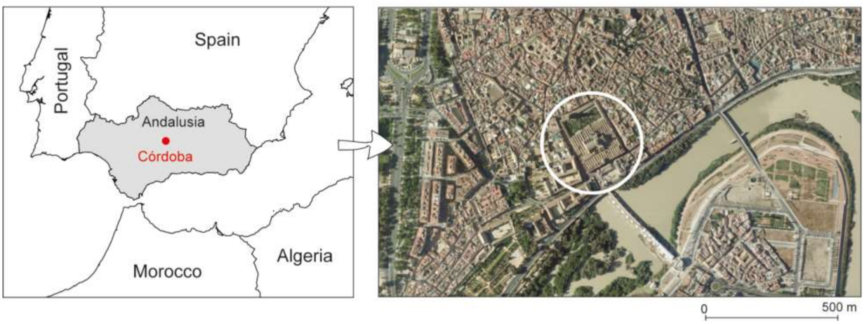

Figure 1. Location of the Mosque-Cathedral of Córdoba

The Mosque-Cathedral has endured many transformations including extensions, alterations and reformations, both during the Moslem period and after the Christian conquest of the city. There are four principal elements in its construction (Figure 2.a): the minaret, a patio or *sahn*, a hypostyle hall or *liuán* and a cathedral transept. The hall or *liuán* is a rectangular space with a support system based on double-arched columns (Figure 2.b). In 1521, a choir and chancel were built in the center of the Mosque-Cathedral and together form a Latin cross (Figure 2.c). Visitors access the *liuán* through a door at the top left and exit through the top right (Figure 2.a).

All MicroClimate Stations (MCSs) developed in this study have been discreetly installed inside the *liuán* and transept with exception to one exterior MCS which was placed on the roof of the the Mosque-Cathedral.

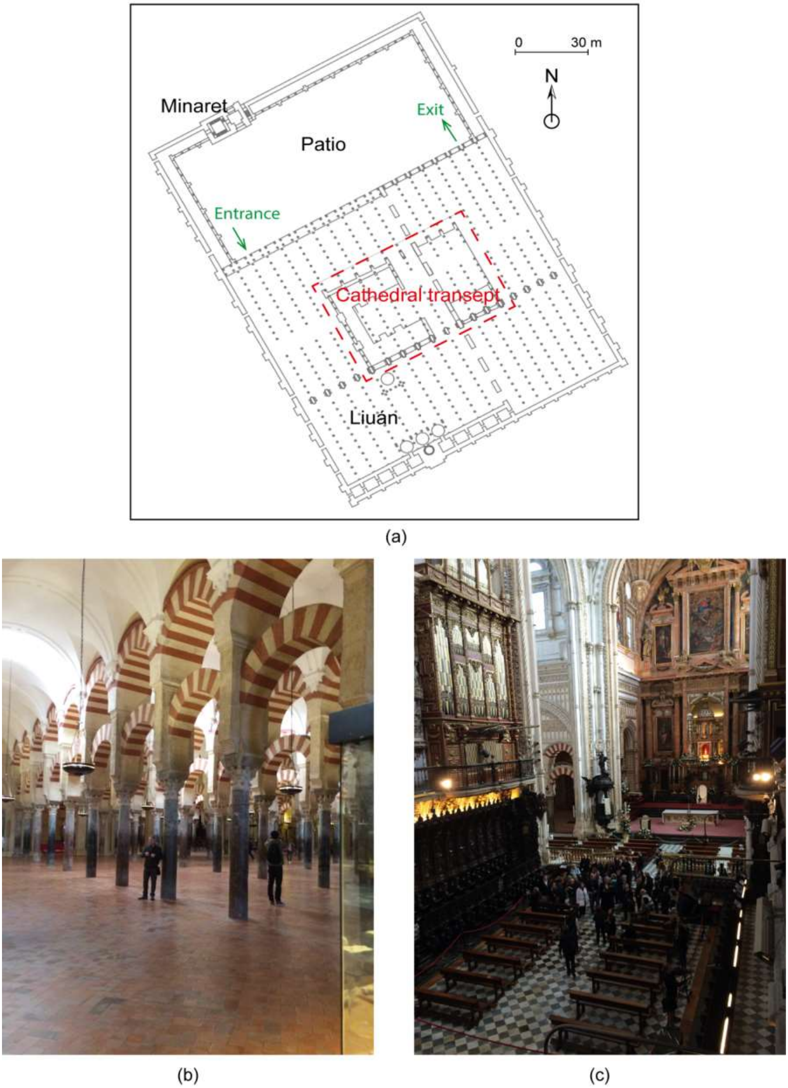

Figure 2. Details of Mosque-Cathedral: (a) key structural elements, (b) *liuán* and (c) Cathedral.

3. Materials and Methods

3.1. Monitoring system

A total of 15 MCSs were installed, 14 in the interior of the Mosque-Cathedral and one on the roof to monitor outdoor weather conditions (Figure 3.a). All MCSs were based on the Arduino platform (www.arduino.cc). Arduino is a single-board microcontroller based on easy-to-use hardware and software. It is a descendant of the open-source Wiring platform and is programmed using a Wiring-based language similar to C++. Arduino boards can be purchased pre-assembled or as do-it-yourself kits with ready access to hardware design information.

In this study, the Arduino UNO R3 [32], a microcontroller board based on the ATmega328 microcontroller, was used. It has the minimal necessary requirements for the study. It contains 14 digital input/output pins, 6 of which can be used as pulse width modulation outputs. Moreover, it has 6 analogue inputs that provide 10 bits of resolution. The ATmega328 also has a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header and a reset button. It has 32 KB of flash memory with 0.5 KB used for boot loading, library storage, as well as the storage of the serial numbers of the sensors and the main program, 2 KB of SRAM and 1 KB of EEPROM.

In the first attempt, a Wireless Sensor Network (WSN) was designed to automatically connect the nodes to each other via wireless link and remote data transmission. However, the wireless link did not work properly because of the thickness of the transept wall which had a width greater than three meters (Figure 3.b). Therefore, each node was set up to work in standalone mode and data were manually downloaded.

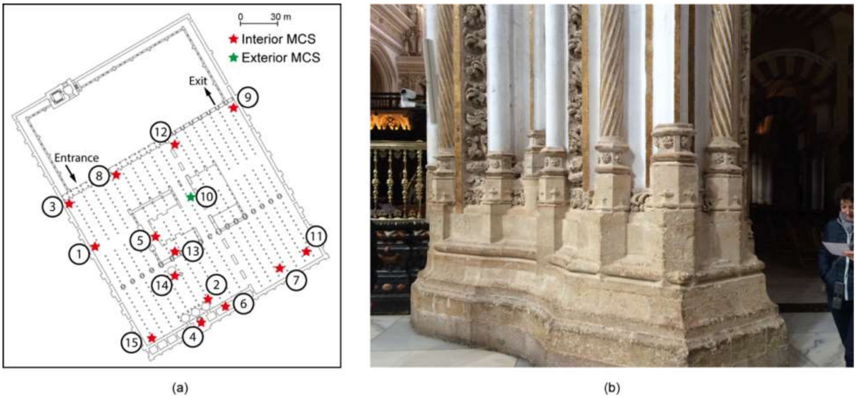

Figure 3. (a) Distribution of MCSs in the Mosque-Cathedral and (b) a photograph of the transept wall.

Figure 4 shows the wiring diagram of a MCS. The role of the microcontroller ATmega328 was to manage, arrange and store the onboard sensor data. Each MCS was scalable and it was possible to include other sensors.In this study, temperature and relative humidity sensors were used. The sensors were chosen considering ISO standards15757 and 15758[33,34]. These standards define the procedures and instruments used for measuring T and RH in the conservation of cultural property. A summary of these standards can be found in[35], which highlights the measuring range, precision and resolution of these sensors. According to these standards, T sensors have to have an uncertainty of 0.5 K and a resolution of 0.1 K. RH sensors have to have a typical measurement uncertainty of 5% and a resolution of 0.1%.In order to verify that sensors worked properly, they were calibrated considering environmental conditions, as in [17].Ten measurements were taken using a 5-min time interval. A PCE-222 environtmental meter (PCE Instruments Ltd., Southampto, Hampshire, United Kingdow) was used for reference. The outcome was a linear model that improved data recorded by the sensor.

The DHT22 digital sensor was used to measure Relative Humidity (RH) and Temperature (T) [36]. It operates with a voltage supply between 3 and 5 V. It is able to measure RH between 0% and 100%, with an accuracy of ±2% and ±5% - usually at the end of a measuring range,and T with a range between 233.15 to 353.15 K with an accuracy better than ±0.5 K. It provides a calibrated digital output signal, assuring its reliability and stability, using humidity sensing technology and an exclusive digital signal collecting technique. Each sensor is temperature compensated using a calibration-coefficient stored in OTP memory.

Each measurement was temporally referenced with a Real Time Clock DS1307 [37]. It operates with a supply of 5.0 V and can operate between 233.15 to 358.15 K. This device is a low power, full binary-coded decimal clock/calendar with 56 bytes of non-volatile SRAM. It uses a I2C protocol to communicate with the microcontroller and an external battery to guarantee the operation if main power fails.

Each MCS operated in standalone mode. For that reason, each MCS stored the information on an 8 Gb SD-Card and the data was manually downloaded periodically.A 220-5 V transformer in the USB port was used to power each MCS. Due to this, each MCS was installed near a 220v electric power connection.The mechanical structure of each node used was an outdoor waterproof case whose ingress protection was equal to 68. Sensors were installed with adequate ventilation and T and RH values were not altered by the operation of the microcontroller board.

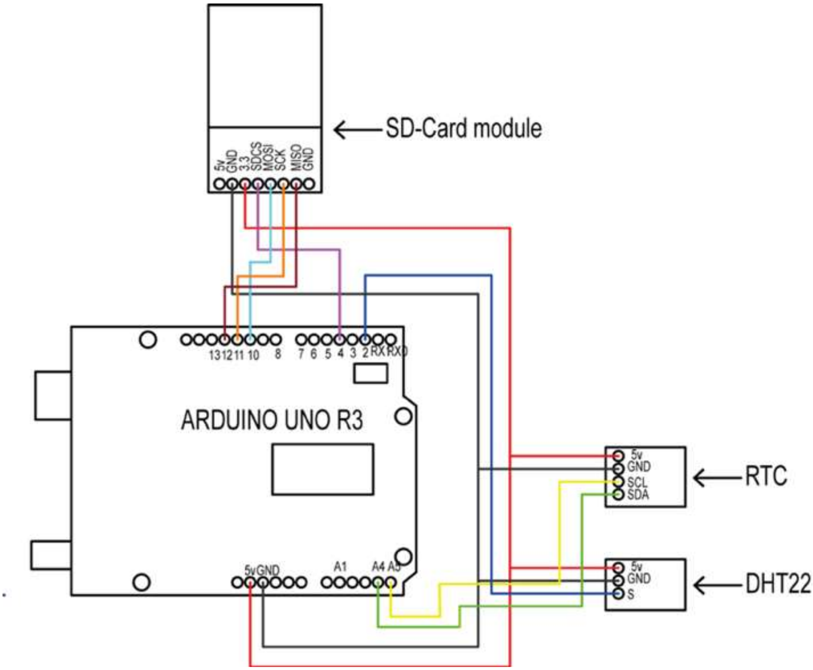

Figure 4. Wiring diagram of a sensor network node with sensors.

3.2Data

All MCSs were installed at the end of December, 2015 with a data acquisition frequency of 1 data package every 2 minutes. Thus, each MCS recorded approximately 21,600 data packages per month. Each data package reported time and date of acquisition, MCS identification, T and RH.

Data were processed in two stages, first to detect anomalous and group data in time intervals equal to 5 minutes, and second, to generate maps and graphs of continuous spatial distribution for each parameter.

In the first stage, an algorithm detected and eliminated anomalous data caused by an error in data collection. Maximum variation allowed per two minutes was set up to equal to ±5 K of T and ±5% of RH as in [38].This anomalous behavior may be due to the sensor itself or to external agents. In the case of the sensor, in addition to the accuracy and precision of sensor itself, it is possible that some components, under certain T or RH conditions, might not work properly. Externally, installed MCSs can be exposed to conditions (people, open door, etc.) that could generate significant variations of T or RH for a short time which are not significant. Therefore, the percentage of eliminated data was 1.2%. Subsequently, data were filtered with a temporal frequency of 5 minutes allowing data to be collected continuously in case a measurement was removed.

In the second stage, data were processed to generate continuous maps showing the spatial distribution of T and RH throughout the Mosque-Cathedral and evolution graphs of T and RH. Triangulation was generated and afterwards a continuous grid was interpolated with a spatial resolution equal to 0.5 meters for each parameter every 5 minutes.

Analysis and processing of data to generate the maps and graphs were done using algorithms developed through Matlab (Mathworks, Natick, MA, United States).

4. Case study and experimental results

On January 1st 2016 all MCSs were installed and began recording data autonomously. From then on, data from each individual MCS were downloaded every week and processed to remove possible outliers. Afterwards, filtered data were used to generate products of interest like distribution maps of T and RH and evolution graphs and plots of T and RH comparing individual MCSs.

Every five minutes T and RH distribution maps were generated from MCSs installed inside the Mosque-Cathedral. These individual maps of T and RH were compiled into video frames to generate an animation of the evolution and dynamics of these parameters over time. It also highlighted the differences of T and RH, while delimiting superfluous behavior, and therefore facilitating technical analysis.

The generated maps reflected the behavior of RH and T and how these parameters were influenced by the interior design of the Mosque-Cathedral, exterior weather conditions and visiting hours. Figure 5 shows a distribution map measuring (and demostrating typical) T and RH values every 6 hours on March 10th 2016. Figure 5.a shows RH started high in the center of the Mosque-Cathedral and, as the day progressed, RH increased and expanded from this point to the lower left corner. Meanwhile, the right side of the building showed lower values. Figure 5.b shows the evolution of T. In this case, higher temperatures were concentrated in the center and bottom half while having a radial distribution.

In general, both T and RH increased as the inner interior of the building was approached. Moreover, these maps show the transept of the Cathedral directly influences the dynamics of the RH. Furthermore, the higher temperature area appears in the lower region of the building. This location is home to an exhibition area of culturally interesting items which are protected by illuminated glass cases whose spotlights may be the cause of these higher temperatures.Moreover, visitors may increase T and RH values in this area in certain moments due to the fact that they remain longer in this exhibition area than in the rest of Mosque-Cathedral.

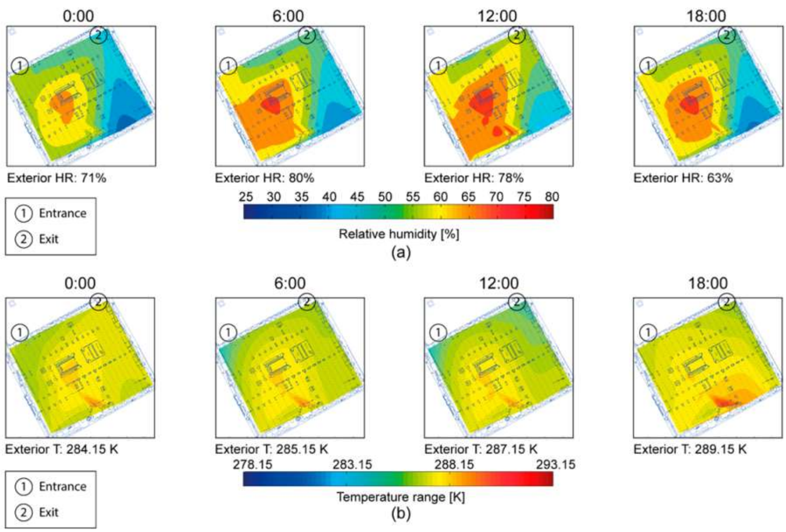

Figure 5. Evolution of distribution: (a) relative humidity and (b) temperature on March 10th 2016.

A piori, the behavior of T and RH inside the Mosque-Cathedral is influenced by exterior weather conditions but the degree of influence is unknown. Due to this, a comparison of the exterior MCS and interior MCSs was done. Table 1 shows statistics of T and RH based on data registered by the MCSs installed in the corners of the interior of the Mosque-Cathedral (MCS 3, 9, 11 and 15) and outside (MCS 10). Analyzing T, MCS-9 (upper right corner) registered values quite similar to those registered by MCS-10. MCS-9 showed a mean value equal to 285.95 K and a standard deviation equal to ±1.5 K. On the other hand, MCS-3 (upper left corner) registered a mean value equal to 286.45 K and a lower standard deviation equal to ±0.9 K. MCSs 11 and 15 registered similar mean values: 287.05 K, but MCS-11 showed the most stable behaviour with a standard deviation equal to ±0.7 K. Behaviour of T inside and outside the Mosque-Cathedral were similar when considering mean values but interior conditions of the Mosque-Cathedral were more stable, showing lower values of standard deviation compared to exterior conditions. On the other hand, although interior MCSs showed similar mean values of T, there were differences in standard deviation. In the first analysis, MCSs installed on the left side had a standard deviation lower than ±1 K, meaning that dynamic temperatures range is lower in this area of the Mosque-Cathedral. Taking RH into account, there are more evident differences between the interior and exterior. Outdoor conditions showed a broad range of RH, mean values was equal to 79.4 % and the standard deviation ±12.7 %. Inside the Mosque-Cathedral, MCS-15 (lower left corner) registered the highest mean RH value: 63 %, and the most stable behavior with a standard deviation equal to ±5.0 %. The lowest values of RH occurred in the lower right corner, MCS-11, with a mean value equal to 51.0 % of RH and a standard deviation of ±8.0%. Intermediately there were MCSs installed in the upper area, MCS-3 and 9, with a RH close to 56%.

Table 1. Statistical summary of Temperature and Relative Humidity statistic inside (MCS 3,9,11,15) and outside (MCS 10) the Mosque-Cathedral.

	Temperature [K]				**Relative Humidity [%]**			
MCS	**Min**	**Max**	**Mean**	**SD[1]**	**Min**	**Max**	**Mean**	**SD[1]**
3	284.15	289.15	286.45	±0.9	34.0	81.5	56.0	±7.3
9	278.15	292.15	285.95	±1.5	27.0	76.6	55.8	±8.0
11	285.15	292.15	287.05	±1.1	29.0	64.3	51.0	±8.0
15	283.15	289.45	287.05	±0.7	35.3	84	63.0	±5.0
10	279.15	294.15	286.05	±2.1	36	99	79.4	±12.7

[1] Standard Deviation

Figure 6 shows an RH and T time series comparison of exterior weather conditions and interior microclimatic conditions, specifically, comparing MCS-10 (exterior) against MCS-9 (interior), which is nearest to the exit, MCS-3 (interior), which is nearest to the entrance, MCS-11 (interior), which is at the lower right corner and MCS-15 (interior) which is furthest from exterior influences (see distribution of MCSs in Figure 3.a).

In considering RH (Figure 6.a), exterior MCS-10 showed (black line), in general, cyclical night and day behavior of RH. Between the 21st and 26th of March, 2016, the differences between night and day are not clearly reflected because it was raining during this period and thus RH showed stable behavior. In the case MCS-15 (blue line, Figure 6.a) was defined by a line close to the minimum values of the RH of the exterior MCS-10. In this case, the evolution of RH does not define a pattern as in the above case, but instead reflected more stability. It should be noted that there were some peaks of higher values of RH in the beginning of the time period unrelated to external weather conditions registered by MCS-15 from the 16th to the 17th of March, 2016. MCS-11 (green line, Figure 6.a) recorded the lowest RH values while MCS-9 (red line Figure 6.a) and MCS-3 (orange line, Figure 6.a), recorded intermediate values between MCS-15 and 11. However, analysis of these data should take into account, as shown in Figure 5, the different behaviors between the left and right side of the building.

Regarding T, exterior MCS-10 (black line Figure 6.b) again showed cyclical behavior. MCS-9 displayed similar results but with reduced differences between maximum and minimum values of T (red line Figure 6.b). Moreover, maximum T registered by MCS-9 are close to those registered by the exterior MCS-10. This was not the case with minimum values. These temperatures are linked to night periods, when the building is closed, showing that the building keeps a stable T. MCS-15 (blue line Figure 6.b) also showed similar behavior to MCS-9, but, in this case, maximum values of T were lower than those registered by MCS-9. MCS-3 (orange line, Figure 6.b) and MCS-11 (green line, Figure 6.b) showed intermediate behaviour between MCS-9 and MCS-15.

As with the RH parameter, the heritage-building keeps constant behavior. These graphs indicate that, in general, the innermost part of the building is cooler to its respective exterior conditions, probably due to the large stone walls that surround it.

Along with the time series graphs of RH and T, we generated plots of evolution of RH and T for each individual MCS. These plots show the evolution of RH and T of individual days and along a three and a half month period, from January 1st to April 15th 2016 (Figure 7). In these plots, the X-axis represents time, 0:00 to 24:00, and the Y-axis represents the day of the year. These plots were used to make a global visual comparison of all the MCSs. Moreover, they were used to study individual behaviors of the MCSs.Figure 7 presents results from interior MCSs 3, 9, 11, 15 of the Mosque-Cathedral and MCS-10 (exterior).

In general, MCS-15 (Figure 7.a) registered higher temperatures and had a more stable range of temperatures than the other MCSs. The maximum hourly average was 287.75 K at 17:00. This MCS registered higher T values than MCS-10 with a maximun mean difference of 275.35 K at 08:00. From this moment, differences started to decrease progressively until 17:00, at which time exterior and interior T values were equals until 20:00, then MCS-15 started to register higher T values. MCS-11 (Figure 7.c) showed a similar behaviour as MCS-15, registering a maximum mean T value equal to 287.25 K at 15:00. Compared to exterior T, MCS-11 registered a maximum difference at 10:00 equal to 274.65 Kand then started decreasing to 273.15 K at 15:00. At this time MCS-11 registered cooler T values than MCS-10, with maximum differences equal to 272.45 K at 21:00. At this time, interior and exterior T differences decreased, being equal to 273.15 K at 01:00. MCS-3 (Figure 7.d), like MCS-15, showed stable behaviour, with a mean value of 286.75 K all the day. Finally MCS-9 (Figure 7.b) showed a broad range of T values and a defined pattern. From 08:00 to 12:00, nearly every day, T values decreased from 285.45 K to 284.05 K. This pattern coincides with opening hours, when the exit door was left open. This MCS registered the most similar values to exterior T, maximum differences being equal to 273.15 K at 06:00 and 272.15 K at 18:00.

Analyzing RH, MCS-15 (Figure 7.a) showed a reduced range in value, around 63%, and lower than those registered by MCS-10 (Figure 7.e). Differences with exterior conditions covered a range of values from -20.7% at 08:00 to -10.6% at 19:00. On the other hand, MCS-9 (Figure 7.b) registered values of RH from 53.1% at 20:00 to 60% at 9:00, showing unstabled behaviour compared to MCS-15. Range of RH differences between MCS-15 and 9 was from -4% at 08:00 to -8.5% at 19:00. Conversely, MCS-3 showed stable behaviour like MCS-15 but with lower RH values, about 56.7%. Finally, MCS-11 registered minimum mean values of hourly RH, being equal to 46.7% at 08:00. Maximum mean hourly values were registered at 17:00, being equal to 51.1%. Both MCS-9 and 11 showed broader ranges of RH values compared to MCSs installed in the left side of the Mosque-Cathedral (MCS-3 and 15).

During the third week of the year, interior MCS plots showed lower RH values that correlated with those reported by the exterior MCS. This behavior was more accentuated in MSC-9 (Figure 7.b). In general, MCS-15 (Figure 7.a) registered higher temperatures than MSC-9 (Figure 7.b), and had a more stable range of temperatures. Contrariwise, MSC-9 had a broad range of T values and a defined pattern. From 08:00 to 12:00, nearly every day, T values decreased. This pattern coincides with opening hours when the doors are left open. A similar pattern is observed analyzing RH plots. MSC-15 (Figure 7.a) shows a reduced range value. During the third week of the year, the plot shows low RH values that correlated with those reported by the exterior MCS, again being more accentuated in MSC-9 (Figure 7.b). Therefore, the resulting data from MCS-9 demonstrates a correlation between climatic conditions of the exterior and interior of the building. This effect is reduced and RH and T values are more stable as the inner interior of the building is approached.

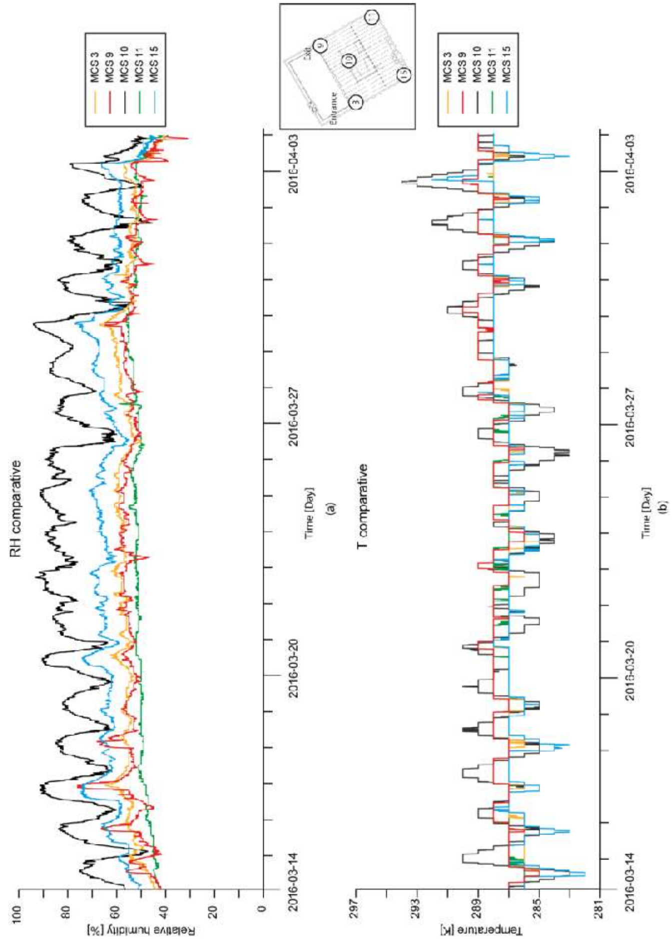

Figure 6. Example time series graph comparing the evolution of (a) RH and (b) T of exterior weather conditions (MCS 10) and interior microclimate conditions of the Mosque-Cathedral (MCS 3, 9, 11 and 15).

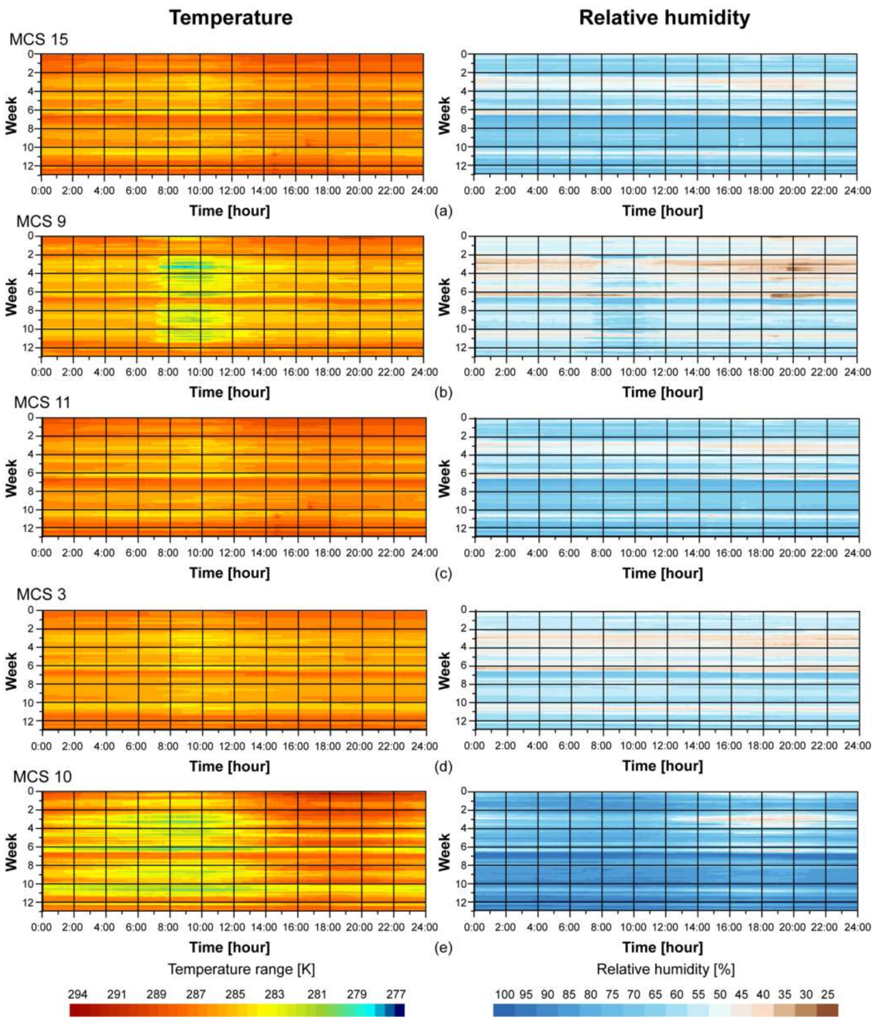

Figure 7. Time plot of RH and T every 5 minutes of interior MCSs: (a) MCS-15, MCS-9, MCS-11 and MCS-3 and (b) exterior MCS-10.

After analyzing the results, the behavior of RH and T inside the Mosque-Cathedral are directly affected by exterior weather conditions. However, the right side of the building showed different behavior in respect to the left side. This may be due to the design of the Mosque-Cathedral's entrance and exit. The entrance is an automatic sliding glass door which controls visitors' access (Figure 8.a) and keeps interior conditions from being affected by external weather conditions. The exit area, on the other hand, is a door which is left open during visiting hours (Figure 8.b) allowing external weather conditions to be more markedly influential in this part of the building.

(a) (b)

Figure 8. Photographs of (a) the entrance to the Mosque-Cathedral and (b) the exit.

Thus, external air currents and the RH and T from exterior weather conditions directly affect the interior microclimate and appears to be channeled by the right wall of the transept of the Cathedral. In the case it is necessary to maintain more homogeneous microclimatic conditions inside the Mosque-Cathedral, installing an automatic sliding glass door like that of entrance may be a suitable solution.Other interventions can be moving visitors exit or delaying the opening hours. Related to the hot spot of the exhibition area, it might be appropriate to revise the lighting system in order to decrease the temperature in that area. Therefore, controlling indoor conditions can be based on a passive microclimate control as a first phase. In this case, indoor conditions would be controlled by the building itself and the outdoor climate. In practice, control should be enhanced by keeping doors and windows opened/closed. Automatic sliding glass door would maintain a more stable interior T in the upper right corner of the Mosque-Cathedral and therefore values of T would increase. This would increase T in the entire right side.Moreover, increasing T would increases RH values, which would be important to consider at opening hours

Technologically, humidity could be controlled by releasing water vapour to the air if the RH is too low (humidification) or by removing water vapour from the air if the RH is too high (dehumidification). In the case of humidication, it is a method for increasing RH. It could be performed by injecting steam into the air or by evapotation of water. In this caseT decreases because the system cools the air, and therefore, a system to heat the air may be neccesary to keep T. Dehumifidication is a method for decreasing RH. It could be performed by condensation or adsorption. Another alternative is to develop a system of heat conservation in order to keep the relative humidity below given limits, although it may cause uncomfortable temperatures and high energy consumption.In this system, T is continuosly adjusted and not maintained at a constant value.

[39] Proposed a system focused on equal-sorption humidity controlling humidifier and dehumidifier devices.The system adjusts the relative indoor air humidity to a level continuosly adapting to the indoor temperature. The objective is to prevent moisture sensitive materials swelling or shrinking caused by changes in the absorbed moisture content. The stabilisation of moisture content in order to determine the RH value is based on T and the logarithmic Herderson model which describes the equilibrium moisture content. The proposed system is more sensitive to changes in air humidity that to variations in temperature.

Regarding the number and distribution of MCSs, this case study has separated zones of the Mosque-Cathedral taking into account T and RH values. Future improvements of the network should be taken into account to increase the number of MCSs to allow a wireless network between nodes. Therefore, although it would be necessary to check connectivity, new MCSs should be installed in the corners of the transept walls to facilitate remote data transmission allowing the design of a real-time monitoring system to provide data for a microclimate system.

Additionally, new MCSs should be installed on right side of the Mosque-Cathedral because this area showed different behaviour compared to left side and currently is monitored with fewer MCSs than the left side.

5. Conclusions

A system to monitor microclimate variables in heritage buildings using OSH was developed. OSH characteristics, such as low acquisition costs and easy customization, can eliminate obstacles associated with proprietary systems. The microclimate information described in the present work shows the behavior of T and RH inside the Mosque-Cathedral of Córdoba and its relationship to exterior weather conditions. The MCSs used have been able to quantify the effects of exterior conditions on interior T and RH of the Mosque-Cathedral, providing useful information for its conservation.

The results of these techniques have revealed how RH and T parameters had a defined behavior pattern. Those areas closest to doors present less T and RH and as the inner interior is approached, these parameters increase. Moreover, these differences are greater when the heritage-building is open to the visitors. Once it is closed, they are reduced. It was also noted that exterior weather conditions directly influence interior conditions and are more pronounced in areas closest to the exit.

The entire system has been developed using OSH. In the future, new sensors can be installed to measure other variables like percentages of carbon monoxide or sulfur dioxide in the air, among others, and their relationship with the volume of visitors.

Acknowledgments: The authors would like to thank the Cabildo Catedralicio of Córdoba for support this Project.

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The Development of an Open Hardware and Software System Onboard Unmanned Aerial Vehicles to Monitor Concentrated Solar Power Plants.

Abstract

Concentrated solar power (CSP) plants are increasingly gaining interest as a source of renewable energy. These plants face several technical problems and the inspection of components, such as absorber tubes in parabolic trough concentrators (PTC), which are widely deployed, is necessary to guarantee plant efficiency. This article presents a system for real time industrial inspection of CSP plants using low-cost, open-source components in conjunction with a thermographic sensor and an unmanned aerial vehicle (UAV). The system, available in open-source hardware and software, is designed to be employed independently of the type of device used for inspection (laptop, smartphone, tablet or smartglasses) and its operating system. Several UAV flight missions were programmed as follows: flight altitudes at 20, 40, 60, 80, 100 and 120 m above ground level; and three cruising speeds: 5, 7 and 10 m/s. These settings were chosen and analyzed in order to optimize inspection time. The results indicate it is possible to perform inspections by UAV in real time at CSP plants as a means to detecting anomalous absorber tubes and improving the effectiveness of methodologies currently being utilized. Moreover, aside from thermographic sensors, this contribution can be applied to other sensors and can be used in a broad range of applications where real time georeferenced data visualization is necessary.

Keywords: UAV, monitoring, open hardware, concentrated solar power

Resumen

Las plantas de energia termosolar de concentracion (CSP) están ganando cada vez más interés como fuente de energía renovable. Estas plantas se enfrentan a varios problemas técnicos de inspección de los componentes, como los tubos de absorción en los concentradores parabólicos (PTC), necesario para garantizar la eficiencia de la planta. Este artículo presenta un sistema para la inspección industrial en tiempo real de plantas CSP utilizando componentes de código abierto de bajo costo junto con un sensor termográfico y un vehículo aéreo no tripulado (UAV). El sistema, disponible en hardware y software de código abierto, está diseñado para ser empleado independientemente del tipo de dispositivo utilizado para la inspección (laptop, smartphone, tablet o smartglasses) y su sistema operativo. Se realizaron varias misiones de vuelo de UAV programadas a alturas de vuelo a 20, 40, 60, 80, 100 y 120 m sobre el nivel del suelo; y tres velocidades de crucero: 5, 7 y 10 m / s. Estos ajustes fueron seleccionados y analizados para optimizar el tiempo de inspección. Los resultados indican que es posible llevar a cabo inspecciones en UAV en tiempo real en plantas CSP como medio para detectar tubos de absorción anómalos y mejorar la eficacia de las metodologías que se están utilizando actualmente. Además, aparte de los sensores termográficos, esta contribución puede aplicarse a otros sensores y puede utilizarse en una amplia gama de aplicaciones en las que sea necesaria la visualización en tiempo real de datos georeferenciados.

1. Introduction

The constantly growing global energy demand and increasing effects of climate change have resulted in the promotion of renewable energy sources to reduce CO_2 levels [1]. Solar technologies are a promising renewable resource because of their ever-increasing output efficiencies and ability to be used in a variety of locations [2]. Solar energy can be converted into electrical energy with different technologies like Photo-Voltaic (PV) panels [3], Concentrating Solar thermal Power (CSP) [4] and Concentrator Photovoltaics (CPV) [5]. Among them, CSP plants are a promising source of renewable energy to be used for predictable utility-scale power generation [6]. CSP plants utilize heat generated by solar irradiation which is concentrated on a small area. Currently, there are four available CSP technologies: Parabolic Trough Collectors (PTC), Solar Power Towers (SPT), Linear Fresnel Reflectors (LFR) and Parabolic Dish Systems (PDS). Of the four, PTC is the most commercialized CSP technology to date [7], focusing direct solar radiation onto a focal line of the collector's axis [8]. In a PTC CSP plant, the mirrors concentrate the sun's rays on absorber tubes and the working fluid, flowing inside the tubes, absorbs solar energy by convection heat transfer. To reduce heat losses, the absorber tubes are enclosed by an antireflective-coated borosilicate glass envelope [9] (Figure 1). Owing to weather conditions and extremely non-uniform heat flux, absorber tubes are subjected to thermal stress resulting in the rupturing of the glass envelopes causing heat loss [10], presenting a problematic challenge. Papaelias et al. (2016)

[6] analyzed and evaluated non-destructive inspection techniques for CSP plants. These techniques are grouped into Liquid Penetrant Inspection (LPI), Magnetic Particle Inspection (MPI), Magnetic Flux Leakage (MFL) and Visual Inspection (VI). LPI is a visual technique based on spreading special dyes over the area for inspection. It is very sensitive to small defects and the inspection is fast but, due to the large quantity of components in a plant, a considerable amount of time is needed for thorough inspection. The MPI technique magnetizes the surface area of the tubes which has been previously sprayed with ferrous particles for inspection. The MFL technique is based on magnetizing the ferrous components for inspection with a magnetic field. Finally, VI of structural components is performed by personnel walking through the plant or by pipe crawling inspection robots. LPI and MPI techniques cannot be used for absorber tube inspection due to the presence of the glass envelope and MFL is not suitable for inspecting absorber tubes of austenitic stainless steel alloy. VI is ineffective as well as there are several kilometers of absorber tubes in a plant to be inspected. However, as the thermal losses are correlated directly with the glass of the absorber tubes, which can be measured using a thermal sensor [11,12], a more efficient alternative to VI inspection is to use robots. In CSP plants, depending on the inspection requirements, these robots can be ground and climbing robots [13]. VI inspections use mainly RGB sensors to evaluate geometrical characteristics [14,15] and thermal sensors to detect heat loss [16,17].

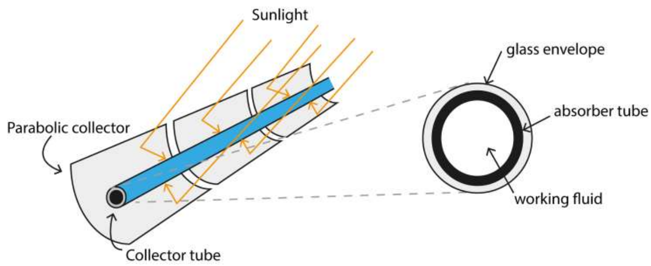


Figure 1. Illustration of functioning parabolic collector and absorber tube

In the last decade, the interest of using Unmanned Aerial Vehicles (UAVs) by professionals and researchers has increased, being applied to replace human activities of a dirty, dangerous and/or, dull nature [18]. In this context, the use of UAVs has become widespread in civil applications such as precision agriculture [19,20], emergencies [21], archaeology [22,23], traffic monitoring [24,25] or visual inspection, [26,27] among others. Relative to industrial inspection, UAVs have been successfully used in monitoring power lines [28], gas pipelines [29] or photovoltaic plants [30]. To our knowledge, no detailed investigation has been conducted regarding the use of UAVs to monitor absorber tube heat loss in CSP plants using PTC technology.

To date, the main problems of current implementations of UAVs are the limited flight autonomy and the size-to-payload ratio [31]. Recent progress in electronics, wireless communications and the production of small-sized sensors offer new opportunities to monitor and control crops, cities, homes and the environment [32]. In this context, the design and implementation of a light-weight payload for UAVs can facilitate CSP plant inspections [33,34]. While there are complete thermographic systems already integrated with UAVs, they are not only expensive, but also closed systems having little capacity for modification and variation [35]. Open Source Hardware (OSH) can be an alternative to closed systems when customization is necessary. Although OSH is quite new compared to Open Source Software (OSS) [36], it is already being used for different applications in agriculture [37], management sensors [38], monitoring heritage buildings [39] or chemical instrumentation [40], among others. In reference to UAVs, some researchers have developed unmanned aerial platforms based on OSH autopilots [41,42] and others have used OSH to integrate and use sensors for data-collection needs [43].

This manuscript describes a system which integrates information registered by a thermographic sensor and geolocation information from OSH components to be accessible in real time by users independently of the type of device used to monitor the inspection (laptop, smartglasses, smartphone or tablet) and its operating system. Its practicality is demonstrated in its application of monitoring absorber tube heat loss in a PTC CSP plant.

The article is divided in the following sections: in Section 2 we present the system; in Section 3 we describe the technical implementation; in Section 4, some field tests and their results are presented, followed by a conclusion.

2. System overview

Figure 2 shows the conceptual model of the system. It has two main components (Figure 2.a): The main system, a camera sensor connected to the developed device, called Khepri, using OSH. In this project a thermal sensor was used, but it is possible to use RGB or multispectral sensors for other applications. Meter accuracy will be sufficient enough to geolocate the thermographic video allowing the thermal sensor to be placed over the Khepri. Both components work synchronously to generate two principal data packages (Figure 2.b). First is the thermal video registered by the sensor while the second is the georeferenced information generated by the Khepri. These two data packages are processed to display three windows on a device screen (Figure 2.c). The first window shows the information registered by the thermal sensor, the second georeferences the system on a cartograph and the third shows an artificial horizon using orientation information. With this information, users will be able to locate incidents at the plant once they are detected through the position and orientation provided by the Khepri.

The information presented in the windows (Figure 2.c) is generated and diffused in real time and is accessible by various devices (laptop, tablet, smartphone, smartglasses) regardless of the operating system (Figure 2.d). Finally, the main system can be used as the payload of an Unmanned Aerial Vehicle (UAV), as well as installed on a terrestrial vehicle or used by personnel (Figure 2.e). The electronic components of the the Khepri were chosen considering the restrictive load capacity of the three aforementioned platforms in both weight and dimensions. All selected components were based on OSH.

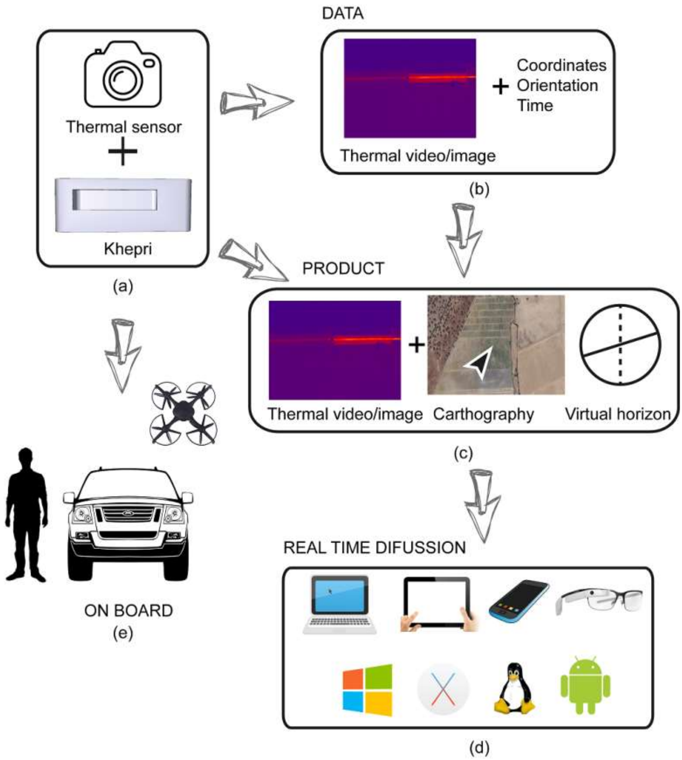


Figure 2. Conceptual model of the system: (**a**) Thermal sensor connected to the Khepri; (**b**) Data package generated by the system; **(c)** Thermal information and georeferentiation of the system over cartograph; **(d)** Real time diffusion regardless of device and operating system and **(e)** working on board multiple platforms.

2.1. Selection of Sensors

Table 1 lists the electronic components and Figure 3 shows a diagram of all the electronic components used in this project. In this study, the Raspberry Pi 2 Model B [44] was used as a single-board computer and the Arduino UNO R3 [45] was used as the microcontroller board. The Raspberry Pi 2 Model B contains a System on a Chip (SoC) Broadcom BCM2836 which includes a 900 MHz ARM Cortex-A7, 1 Gb Synchronous Dynamic Random Access Memory (SDRAM), 4 Universal Serial Bus (USB) ports, 1 High-Definition Multimedia Interface port (HDMI), 1 micro Secure Digital (SD) to store information and 1 Ethernet port. The Raspberry Pi stores the video registered by the connected sensor. The Arduino UNO R3 is a microcontroller board based on the ATmega328 microcontroller which manages and arranges the onboard sensor data. It has the minimal requirements for the study containing 14 digital input/output pins, six of which can be used as pulse width modulation outputs, 6 analogue inputs, an ATmega328 microcontroller with an 18 MHz crystal oscillator, a USB connection, a power jack, an In Circuit Serial Programming (ICSP) header, 32 KB of flash memory, 2 KB of SRAM and 1 KB of EEPROM (Electrically Erasable Programmable Read-Only Memory).

A GPS Shield based on the ublox NEO-6M receiver module [46] is used to obtain the coordinates of the device. The positioning engine uses 50 channels and measures time based on Time To First Fix (TTFF) of less than 1 second, searching in parallel both time and frequency space, allowing instant satellite discovery. The horizontal position accuracy is 2.5

m, sufficient for this study. The 3-axis digital accelerometer ADXL 345 [47] was used to measure static acceleration as tilt and dynamic acceleration to determine the attitude of the system. It has an output resolution equal to 10 bits and a sensitivity deviation from ideal equal to ±1%. Each data package was temporally referenced with a DS1302 real-time clock [48]. It operates with a supply of 2 to 5.5 V and can operate between 0°C to +70°C. It contains a real-time clock/calendar and 31 bytes of static RAM.

A USB modem was used to upload information generated by the system to the cloud to be diffused to other users. Finally, a LCD Screen 1602 [49] was used to display battery percentage and the verification of all the components. It operates with a supply of 5 V. A rechargeable 7.4 V LiPo Battery with 1400mAh capacity was used to power the system.

All the electronic components were distributed inside a PolyLactic Acid (PLA) case printed by a 3D printer. PLA material is a biodegradable polymer harder than other materials like Acrylonitrile Butadiene Styrene (ABS), melting at lower temperatures (from 180°C to 220°C), with a glass transition temperature around 60°C. The PLA case dimensions are 132x132x47 mm and its weight is equal to 50 gr. The total weight of the device is 375 gr in addition to the thermal sensor weight, in this case, 263 gr.

Table 1. Khepri electronic components.

Title 1	Weight (gr)	Dimension (mm)
Raspberry Pi2 Model B	45	85.6 x 56.5
Arduino UNO R3	25	68.6 x 53.4
GPS Shield ublox NEO-6M	32	61.4x53.3x16
Accelerometer ADXL 345	5	3x5x1
DS1302 clock	10	9.91x7.87x4.45
Modem USB	24	88x28x10
LCD Screen 1602	50	80x36x13.5
Lipo Battery	79	125x7x21

2.2 *Technical implementation*

As Figure 3 shows, the Khepri is composed of two main subsystems: the Arduino and the Raspberry Pi connected to an external sensor. The Arduino subsystem manages geo-information data packages generated by GPS and IMUs. The GPS Shield is connected to digital port 0 and 1 of the Arduino UNO board. From the NMEA string, received latitude and longitude are extracted. This information is used to locate the system on a cartograph in real time. An accelerometer ADXL 345 is connected to digital port 2 and analogical port 4 and 5 of the Arduino UNO board. Data from ADXL 345 are converted to yaw, pitch and roll angles allowing the orientation of the system to be known. Both the thermal sensor and the Khepri work simultaneously displaying their respective data packages on screen. Using the coordinates obtained by GPS and orientation by IMUs, the Khepri's location is approximately (≈ 1m) registered to indicate approximately location of the thermal sensor. As such, a user will be able to see, with an external device, live onscreen thermal video in a window along with its geolocation on a cartograph in another window.

As the data is being rendered, the Raspberry Pi collects the information from the thermal sensor and from the Arduino subsystem and makes a backup copy on an SD-Card. From thermal sensor, a thermographic video is stored while the Arduino system creates a log file with geolocation information, allowing the video to be georeferenced for later use if needed.

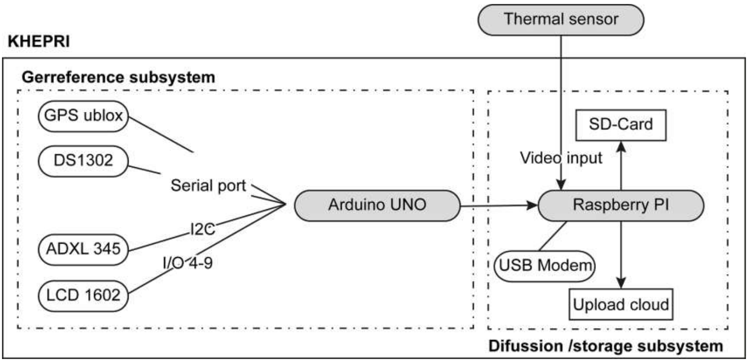


Figure 3. Conceptual model

Two methods have been adopted for the cartographic display: API Google Maps and Leaflet. Public API Google Maps is a set of object classes, functions and data structures applied using JavaScript or other scripting languages [50]. The latest version is supported by traditional web browsers or those implemented on mobile devices. API Google Maps uses cartography from Google Maps. On occasion, the resolution of this cartography is insufficient, either in temporal or spatial terms. For this reason, a web mapping application was developed using the JavaScript library Leaflet [51]. In this research project an ortho-mosaic was produced using RGB images registered by a UAV flight over a CSP plant with a spatial resolution equal to 5 cm. This ortho-mosaic was published through a Web Map Service (WMS) using Geoserver [52] and displayed by Leaflet. With the availability of these options, users will be able to choose the most suitable mapping source.

In short, the Khepri will display three windows: one with thermographic information, the second with a map viewer and the third with a virtual horizon. These windows will be distributed on the screen.

To diffuse information from sensors or devices onboard UAVs in real time, most applications use a radio frequency transmission system that connects the UAV with a Ground Control Station (GCS) [53,54]. Images or video registered by the onboard sensor are transmitted to the GCS and further relayed to other users. On occasion, a lost transmission data link can occur and result in the loss of information sent from the UAV to the GCS [55]. In this developed solution, the system itself has the function of sending the information in real time without needing a GCS to communicate with the users as the Khepri, via USB modem, connects to the Internet, by which the information of interest is transmitted. Therefore, it is necessary to have a solid mobile data link to work in real-time, which is maintained in these plants for security reasons. In other case the inspection can be analysed later using the information registered in the SD-Card.

Two user profiles have been defined for the system: administrator and invited user. The administrative user has system configuration privileges, for example, to control how the thermal sensor works or to interrupt data transmission. These profiles can be applied in two different scenarios. In the first (Figure 4.a), while the system is on terrain, the administrator can connect a screen to the Khepri through the HDMI port, accessing the windows and functions of the system. In the second scenario, the administrator can connect remotely, accessing the Khepri through Chrome Remote Desktop using a Chrome browser with an Internet connection (Figure 4.b). In this case, if there are invited users, they will be able to access the thermal inspection. This is due to the fact that the system, when the administrator chooses, shares the desktop screen live using the application Screenleap (Figure 4.b). Invited users are linked via URL for view only access which allows the system to be accessible regardless of the type of device and/or operating system. This solution guarantees the interoperability of devices and operating systems. It is also worth noting that the number of invited users is not limited. This multi-access to the Khepri allows users work at different locations and with different objectives simultaneously. For example, the UAV operator can perform the flight with focus on guarantying security of the UAV mission while, simultaneously, other users are managing the thermal inspection, whether at the same plant or another country.

Moreover, this activity can be performed by more than one user to guarantee the quality of the visual analysis.

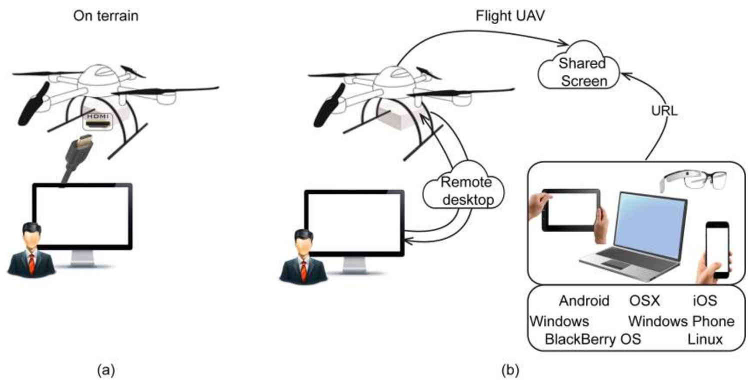


Figure 4. User profiles and cases of use: (a) the administrator sets the system on terrain and (b) the system onboard a UAV flight being accessed by the administrator through remote desktop and invited users with different operating systems accessing inspection via URL.

3. Results

The prototype PLA case measures 132x122x45 mm allowing it to be installed in a UAV gimbal (Figure 5.a) and was designed to be ergonomic, resistant to deformation and low weight. All the components of the Khepri were distributed in such a way that the center of mass is close to the center of the PLA case (Figure 5.b).

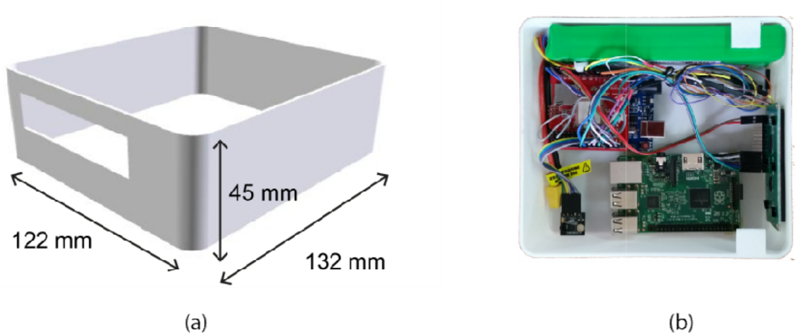


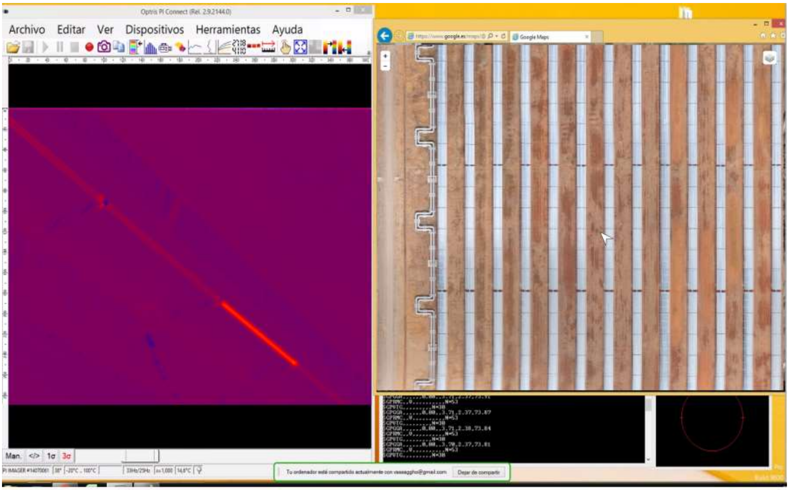
Figure 5. PLA case: (a) Design of prototype and (b) distribution of components

A UAV flight campaign over a CSP plant was executed with two objectives: to verify the system works properly and to test different altitudes AGL and cruising speeds to define the specifications for use. A quadrocopter, model MD4-1000 (Microdrones GmbH, Siegen, Germany) was used as the UAV to perform the flights above the La Africana PTC CSP plant, located in Córdoba, Spain (CSP plant details in [56]) (Figure 6.a). This CSP plant has 104 km of absorber tubes distributed on the surface. Currently, at this CSP plant, a thermographic inspection is performed by a technician with a thermal gun walking through the solar field and inspecting the absorber tubes. Once a problem is detected the incident and its location is noted. With this methodology, an inspection takes a week for an expert technician, two if the inspection is done by a junior technician and is only performed once a month or every two months. These numbers highlight the ineffectiveness of the method.

MD4-1000 is a vertical take-off and landing platform, entirely carbon designed and equipped with 4 × 250W gearless brushless motors powered by a 22.2 V battery. Maximum cruising and climb speeds are 12 m/s and 7.5 m/s respectively. MD4-1000 can operate in remote control mode or automatically. The payload was the thermographic sensor Gobi 640 GiGe (Xenics nv, Leuvem, Belgium) connected to the Khepri (Figure 6.b and Figure 6.c). The Gobi 640 GiGe is an uncooled micro-bolometer sensor that operates in the 8-14 μm spectral band with an image size of 640x480 pixels and a focal length of 18 mm. It is calibrated to operate from -25°C to 125°C with a resolution equal to 50 mK. Figures 6.b and Figure 6.c show a front and back view of the Gobi 640 GiGe and the Khepri onboard the UAV.

Figure 6. (a) The UAV performing an inspection on CSP plant, (b) front view of system onboard the UAV, (c) back view of system onboard.

Figure 7 shows a screen capture from Khepri during a thermal inspection on the PTC CSP plant. The left window contains the information from the thermal sensor showing an anomaly on an absorber tube. Simultaneously, in the right window the system is located on a orthomosaick of the CSP plant. In this example, an orthomosaick produced by an RGB sensor onboard an UAV and published by Leaflet is used to position the system.



(d)

Figure 7. Screen details from Khepri during a thermal inspection on a CSP.

In this study, a set of flight missions were flown at altitudes of 20, 40, 60, 80, 100 and 120 m AGL. The UAV flew in autonomous mode with each flight mission uploaded previously. Each altitude AGL is linked to a specific ground sample distance (GSD) value (Table 2). Additionally, three different cruising speed settings were used: 5, 7 and 10 m/s. Maximum velocity was set to insure the video did not undergo blurring caused by platform movements. All flights were performed under the same conditions, the wind speed being equal to 1 m/s. Table 2 summarizes, for each altitude AGL, the GSD of the video frame and, for each cruising speed, the time, in hours, taken to inspect the entire plant. Duration is expressed apart from the time spent taking off and landing and time to change batteries. In this study, GSD ranged from 1.9 cm × pixel^{-1} at 20 m

AGL, to 11.3 cm × pixel^{-1} at 120 m AGL. Inspection duration ranges from 0.8 hours flying at 120 m AGL and cruising speed equal to 10 m/s, to 5.8 hours flying at 20 m AGL and cruising speed equal to 5 m/s. Table 2 demonstrates that, as altitude AGL increases, inspection duration decreases because each video frame covers more area, monitoring several lines of absorber tubes simultaneously in each lap. This occurs regardless of the cruising speed of the UAV. Altitude AGL and duration inspection show a logarithmic correlation for all cruising speeds equal to 0.869 (Figure 8). Therefore, as altitude AGL was increased, inspection duration logarithmically decreased. In addition, cruising speed was not relevant in detecting anomalies during the inspection due to the great temperature differential of a broken absorber tube.

Table 2. Summary of the unmanned aerial vehicle (UAV) flights.

	UAV Inspection time (hours)			
Altitude AGL (m)	**GSD (cm)**	**5 m/s**	**7 m/s**	**10 m/s**
20	1,9	5,8	4,1	2,9
40	3,8	5,8	4,1	2,9
60	5,7	3,0	2,1	1,5
80	7,6	3,0	2,1	1,5
100	9,4	2,0	1,4	1,0
120	11,3	1,6	1,1	0,8

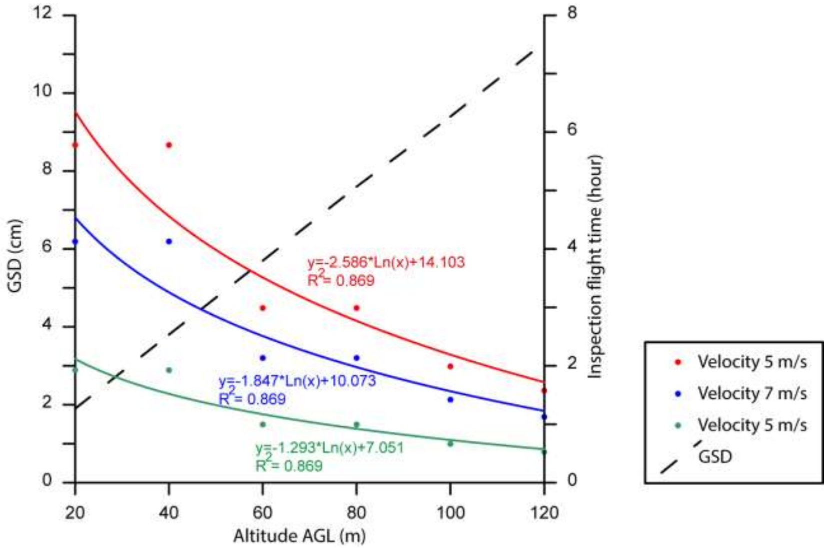


Figure 8. Inspection flight time considering cruising speed and altitude AGL.

As to visual inspection, Figure 9 shows an example of a video frame at 20 m AGL (Figure 9.a.1 and 9.a.2) and 100 m AGL (Figure 9.b.1 and 9.b.2). All considered altitudes AGL detected heat loses from absorber tubes satisfactorily. However, due to the wide range of inspection times, it is necessary to optimize the flight parameters for best results. All positive inspections were caused by the high temperature around the broken absorber tubes. Flying at 20 m AGL (Figure 9.a.1) the thermographic video showed bellows between absorber tubes, making it possible to identify the thermal section along the tube. This high level of detail requires longer UAV flight times at low altitudes AGL. Increasing altitude AGL (Figure 9.b.1) diffuses the image, but the anomaly is still detected, and inspection time is decreased. In both cases, if the histograms of the frames are stretched, the anomalies in absorber tubes are clearly shown independently of altitude AGL (Figure 9.a.2 and 9.b.2).

In summary, as a strategy in a PTC CSP plant inspection, the system can fly at low and high altitude AGL jointly, optimizing UAV flights and therefore time inspection. Firstly, a UAV flight can be executed at a high altitude AGL, detecting absorber tubes which show anomalies, as well as obtaining the percentage of anomalous tubes of the entire CSP plant. Once these are located, they can be viewed at very high spatial resolution to be analyzed with precision by flying at low altitude AGL in specific areas. Using this strategy, it is possible to optimize the number and duration of UAV flights without losing information.

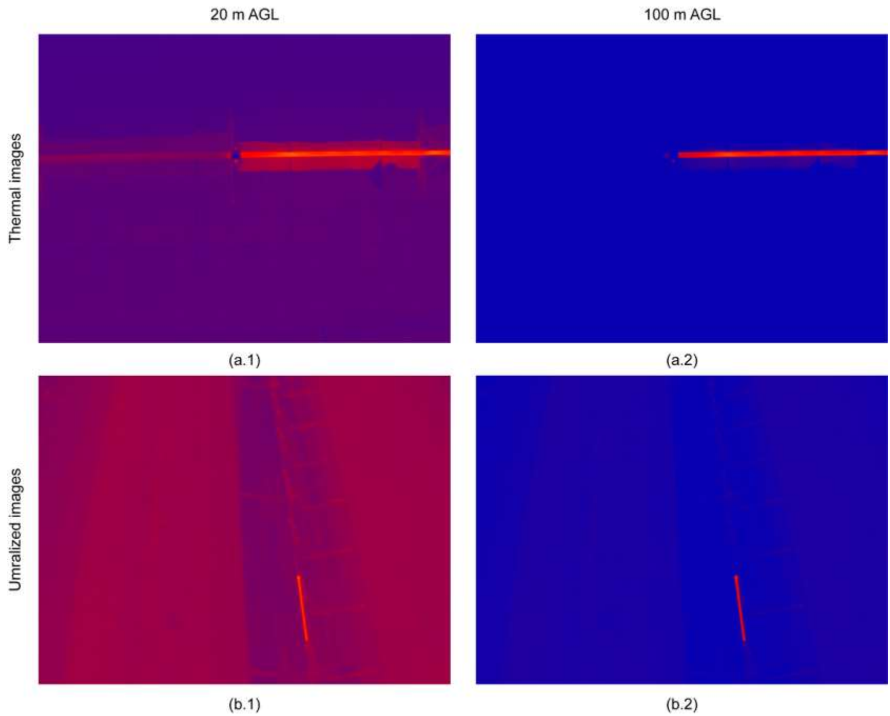


Figure 9. Examples of the UAV inspection at (a) 20 m and (b) 100 m AGL, (1) un-stretched and (2) stretched histograms.

All tests were observed in real-time by different users in different locations and with different devices. The invited users were located both at the CSP plant and our university department. The invited users followed the inspection simultaneously using tablets and smartphones with android and iOS operating systems, laptops with Windows, Linux and OSX and android smartglasses. To connect to the inspection using mobile devices, a QR code was provided with the URL where the Khepri windows were being displayed. Connection tests were successful, with no interruptions occurring during the connection. The administrative profile interacted with the Khepri both directly, before the UAV flights started, and from our university department through a connection by remote desktop.

Considering how van Blyenburgh [18] establishes that UAVs ought to be used for activities which are "dull, dirty and dangerous", and walking inspections are categorically dull, recurring mode UAV flights at a PTC CSP plant fits van Blyenburgh's defined use while at the same time intensifying the cadence of thermal inspection at the plant. Table 3 shows the percentage of improvement in inspection time with the developed system due to its ultra high resolution and speed compared to current methods based on walking inspections at the CSP plant. The improvement of time inspection ranges from 85.6 % flying at 20 m AGL and a cruising speed of 5 m/s to 98.0% flying at 120 m AGL and cruising speed equal to 10 m/s. Independently of altitude AGL and cruising speed used, the developed system allows a more productive method without losing information compared to current methods.

Table 3. Improved productivity of UAV inspection work versus manual inspection.

Altitude AGL (m)	5 m/s (%)	7 m/s (%)	10 m/s (%)
20	85,6	89,7	92,8
40	85,6	89,7	92,8
60	92,5	94,7	96,3
80	92,5	94,7	96,3
100	95,0	96,4	97,5
120	96,1	97,2	98,0

5. Conclusions

A system onboard a UAV to monitor CSP plants using OSH and OSS was developed with customization capabilities depending on use. The thermal inspection of a CSP plant was successful at different altitudes AGL and cruising speeds, and allowed the possibility to observe the inspection using different devices with different operating systems. As result, we propose flights at two altitudes AGL. Firstly, UAV flights at 100 - 120 m AGL to locate incidents on absorber tubes around the plant. Once they are located, a focused inspection at low altitude AGL, 20 m AGL, can be performed to analyze the problem in detail. With this strategy, inspection time is optimized.

The proposed methodology is more efficient than traditional methods based on walking with a thermal gun through the solar plant.

Moreover, the proposed system will allow the numbers of inspections to be increased, improving the efficiency of CSP plants.

The entire system has been developed using OSH and OSS, allowing for customization depending on application. In the future, RGB or multispectral sensors can be used in other scenarios like precision agriculture. Moreover, board computers with higher capacities can be used on the Khepri to process video or images in real time to detect anomalies and sends alerts among other possible uses. This automation would permit the number of experts analyzing the thermal video to detect leaks to be reduced.

Acknowledgments: This research was funded by Khepri project supported by CDTI: Centro para el Desarrollo Tecnológico Industrial, FEDER Funds: Fondo Europeo de Desarrollo Regional and CTA: Corporación Tecnológica de Andalucía. The authors would like to thank Magtel Corporation (Spain) for providing access to La Africana CSP plant.

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Discusión general

La evolución y el desarrollo de la programación y de la electrónica open-source, abren una nueva dimensión para la implementación de estos sistemas de forma global en todo el mercado mundial. Estas plataformas libres están pensadas para todos los colectivos, desde la educación a los campos más específicos, que necesitan de una electrónica solida y duradera, que aporte fiabilidad a los sistemas de control.

El primer paso para el montaje de un sistema open-source es la elección del hardware, éste es el que se programará para que realice el trabajo o la actividad deseada por el usuario. En el **Capitulo 1** de esta tesis se realiza un análisis exaustivo de los sensores existentes en el mercado, para diseñar un sistema que tenga un precio muy económico, sin renunciar a la calidad y precisión de otros sensores de mayor precio. Una vez elegidos estos, se procedió a su calibración y el montaje del sistema. Cada sensor tiene un proceso de calibración y montaje distinto, teniendo que establecer unos protocolos de conexión distintos para cada uno de ellos. Una vez conectados se diseño una estructura que fuera capaz de albergar todo el conjunto de sensores, protegiéndolos del medio ambiente, y de posibles golpes externos. El sistema esta alimentado con una placa fotovoltaica, y una batería, la cual asegura una alimentación continua y autónoma.

La programación del dispositivo tiene dos entornos, uno propio para el funcionamiento del dispositivo, basado en el lenguaje propio de Arduino mediante su SDK. El otro entorno de programación es Java, con el que se crea una aplicación para la gestión del dispositivo de forma telemática.

Una vez listo el dispositivo se procede a la validación del dispositivo, la cual se realizó con una estación meteorológica Davis Vanjage pro 2. Se realizaron varias mediciones durante un dia, quedando constancia de la mínima diferencia entre las medidas de una estación y la otra, con lo que quedó constatada la validez de esta estación montada con open-sorce.

Una vez dispuesta la estación y comprobada su precisión, se procedió a una evaluación de su integridad, para ello se dejo instalada en la finca del Campus de Rabanles de la Universidad de Córdoba, comprobando su funcionamiento de manera autónoma, sin depender de ningún tipo de mantenimiento ni supervisión durante varios meses obteniendo un dato de cada sensor cada hora.

Como conclusión de este dispositivo se puede decir que es una estación robusta y con una buena precisión, además el aspecto mas señalable de instrumento es el precio 10 veces inferior a soluciones comerciales que disponen de unas características similares.

En el **Capítulo 2** de esta tesis se instalan 14 estaciones open-source en la Mezquita-Catedral de Córdoba. La intención de estas estaciones es crear un mapeado multitemporal de la temperatura y humedad de este edificio que pertenece al Patrimonio de la humanidad.

La instalación de las estaciones fue cuidadosamente elegida en distintas partes del edificio, que se estimaba que tenia un comportamiento distinto a otros puntos del emplazamiento, como por ejemplo la entrada o salida de la Mezquita-Catedral. La configuración de las estaciones proporcionaban un dato cada 2 minutos, con lo que se hizo una selección de todos los datos, reduciendo a un dato cada hora. Debido a la cantidad de datos generados se tuvo que generar un programa para generar de forma automática el mapa de temperaturas y humedades, con los datos de las estaciones sobre el plano del edificio.

Estos datos podrán servir para la gestión del patrimonio y la conservación del edificio. Adecuando la temperatura y humedad ambiental, acorde con una conservación positiva con las estructuras arquitectónicas, frescos y demás obras presentes en el lugar.

Como conclusión de estos mapas se puede sacar la gran inercia térmica del edificio, e influencia de las condiciones ambientales del exterior en el edificio, quedando reflejada la zona de la entrada y la salida que tienen una variación de parámetros superior, a por ejemplo la zona interior del edificio.

En el **Capítulo 3** de esta tesis se elabora un dispositivo para la supervisión de centrales termoeléctricas. Actualmente la supervisión de estas plantas corre a cargo de operarios que recorren la plantas con una cámara termográfica, y andando por toda la planta, van analizando cada uno de los tubos que recorren los concentradores parabólicos de la central. Esta tarea que además de tediosa y aburrida es peligrosa podría ser automatizada mediante un vehiculo aéreo no tripulado y un sistema de cámara termográfica georeferenciada.

Actualemte se encuentran sistemas cerrados con estas especificaciones, los cuales además de tener un precio elevado, también presentan el inconveniente de no poder ser modificados ni ampliados por el usuario para modificarlo a sus necesidades.

Por todo esto se contruye un dispositivo, compuesto por una plataforma open-source, con un sensor GPS y un sensor inercial, y una cámara termográfica. Este dispositivo proporciona una imagen en tiempo real mediante un sistema de conexión 3G, de las imágenes obtenidas a partir de la cámara termográfica, con su localización y posicionan en el espacio.

Esto facilita la labor de inspección en grandes plantas donde resulta difícil identificar por la imagen cual es el tubo o el receptor parabólico que se esta observando. Además el ángulo de los espejos que van variando para orientarse de cara al Sol, dificultan la inspección del operario de forma manual. Por ello la isntalacion de este dispositivo en un vehiculo aéreo no tripulado, agiliza enormemente esta labor, primero por la posición sobre los receptores parabolicos, que al estar elevados sobre el suelo, dificultan la visión de los tubos, y segundo por la faciliad y velocidad con la que este vehiculo puede recorrer la central.

Se realizó un estudio de las diferentes alturas y velocidad de vuelo frete a la resolución del sensor termográfico, dando como resultado un ahorro de tiempo frente el método de inspección tradicional.

Como conclusión se puede decir que este sistema ofrece ventajas como el coste económico, y las posibilidades que ofrecen las plataformas open-source a modificaciones, configuaciones y adaptaciones de otros sensores del mercado. Esto da una capacidad superior sobre el resto de sistemas cerrados que se comercializan actualmente.

Conclusiones

A modo de resumen, las conclusiones y consideraciones finales que pueden establecerse de la presente tesis doctoral son las siguientes:

-La tecnología Open-Hardware se encuentra en un momento de plena expansión, pasando de un uso exclusivamente educativo a un uso en el mundo profesional. Este gran auge que experimenta esta plataforma, está relacionada con el bajo coste que tiene respecto a las versiones comerciales que se pueden encontrar el mercado. De los resultados obtenidos de la presnte Tesis se puede afirmar la robustez y la estabilidad de los resultados ofrecidos por la electrónica Open-Hardware. Ha quedado demostrado que no se necesita una electrónica de alto coste para entornos exteriores, los cuales son una prueba de rigor, para asegurar su resistencia a cualquier entorno posible.

La versatilidad que ofrece los sistemas Open-Hardware hacen que esta plataforma tenga una evolución continua, ya que millones de usuarios usan esta electrónica generando un desarrollo exponencial a lo largo del tiempo. Este progreso esta generado por la comunidad de usuarios, que prestan todos sus conocimientos de forma desinteresada al resto de usuarios, los cuales aprovechan esos conocimientos para mejorar sus propios desarrollos. Esto conlleva a una implementación continua de nuevos sensores y nuevas aplicaciones, además de la adaptación propia que cada usuario puede realizar, para que se adapte mejor a las exigencias.

Asociado a este Open-Hardware se encuentra el denominado Open-Software. Este software libre sigue las mismas premisas que el hardware libre, ofreciendo un sinfín de posibilidades, como un SDK para posibles desarrollos propios, o gestión propia de la programación. Este aspecto sumado a la carencia de coste económico que supone el uso de estos sistemas operativos, hace que sean la opción más acertada para afrontar nuevas aplicaciones.

Como parte negativa se establece decir que todas las plataformas que se muestran en esta Tesis necesitan de una experiencia propia y una capacidad para la integración y montaje. Por el contrario los sistemas comerciales que se encuentran en el mercado, son sistemas cerrados y montados listos para funcionar, ahorrando al usuario la fase de calibración y validación de éste.